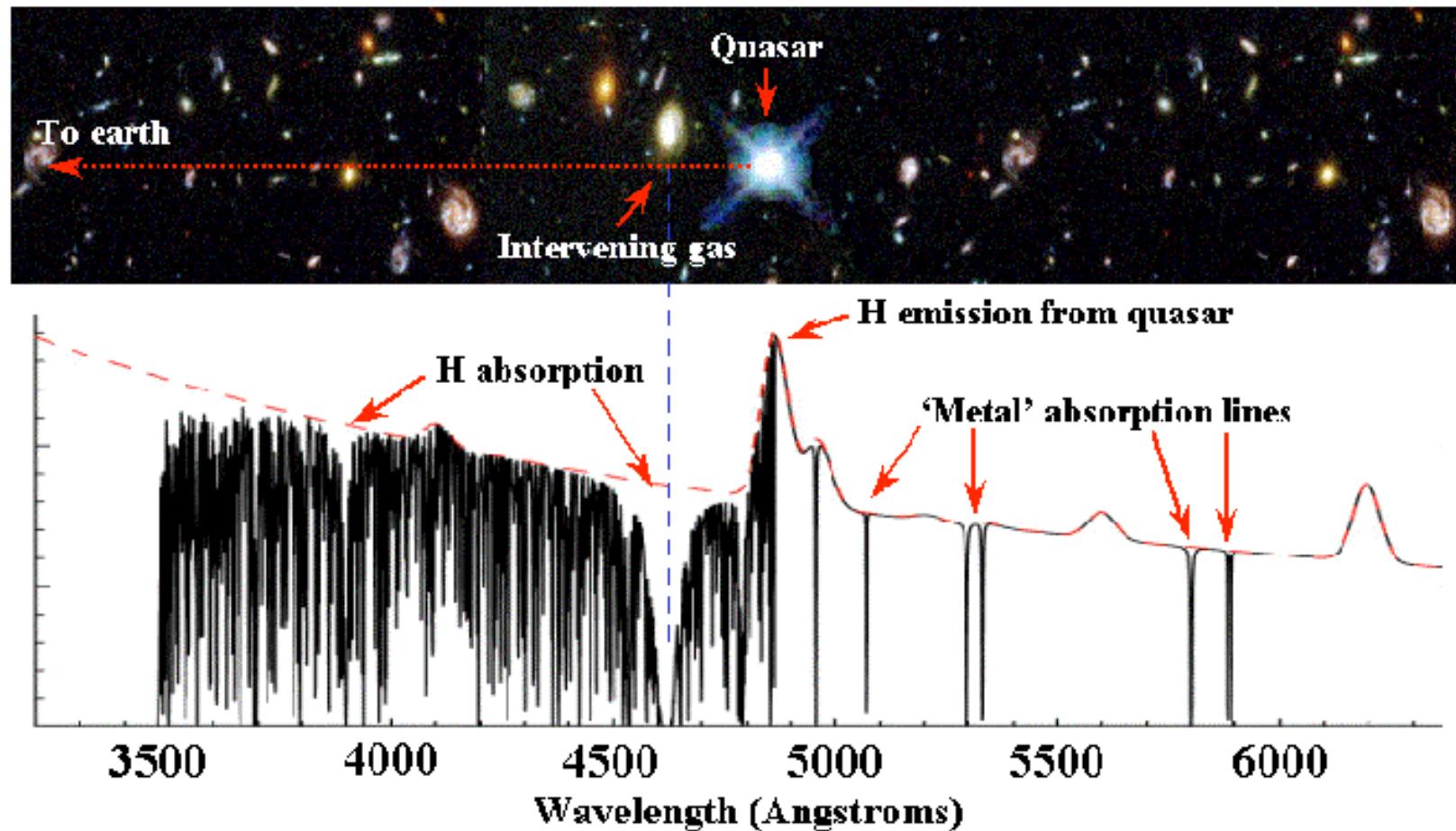


# Physics of The Lyman $\alpha$ Forest

Michael Norman

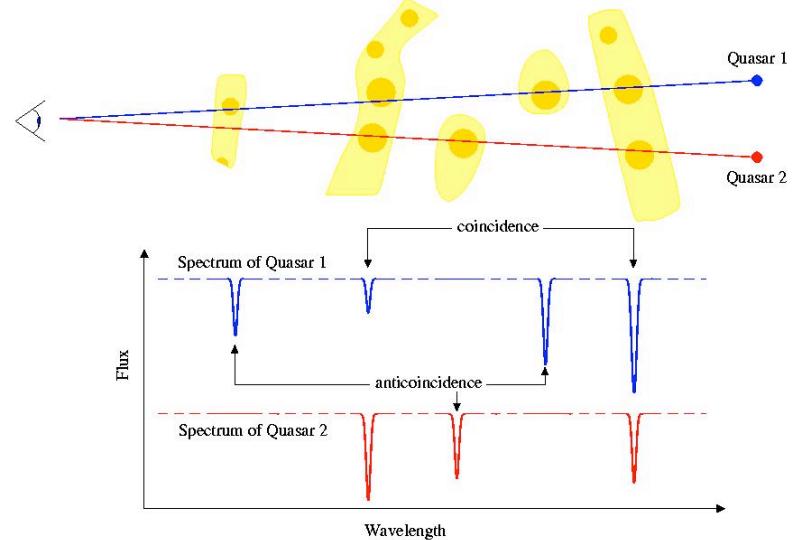
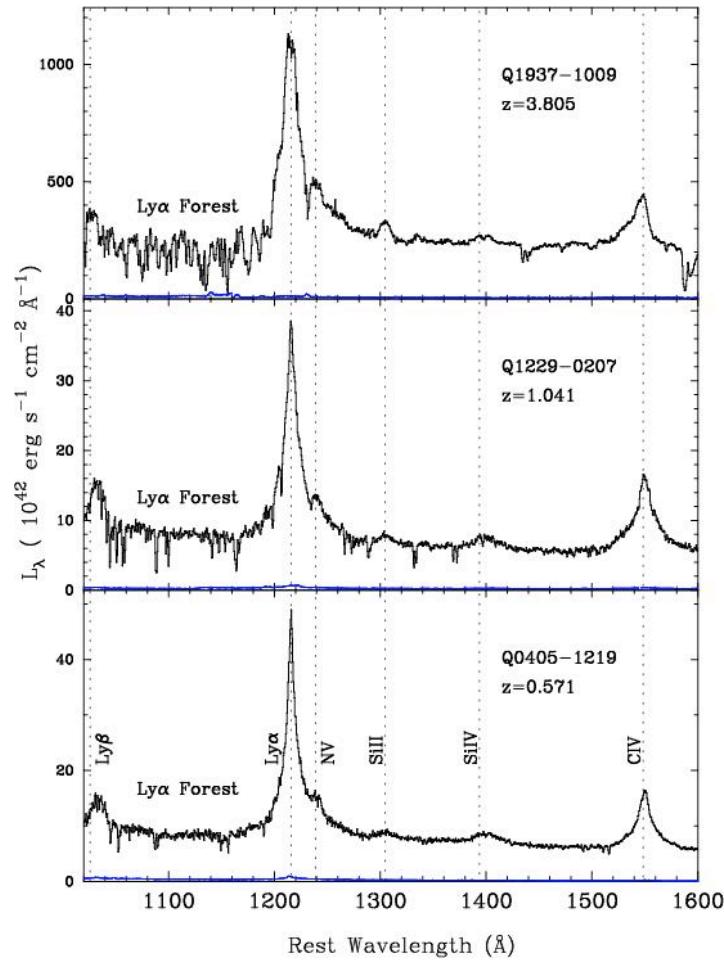
Laboratory for Computational Astrophysics  
UC San Diego

# Quasar Absorption Line Systems



Source: M. Murphy

# Quasar Absorption Lines: Ly $\alpha$ Forest



N. Suzuki PhD thesis (2005)

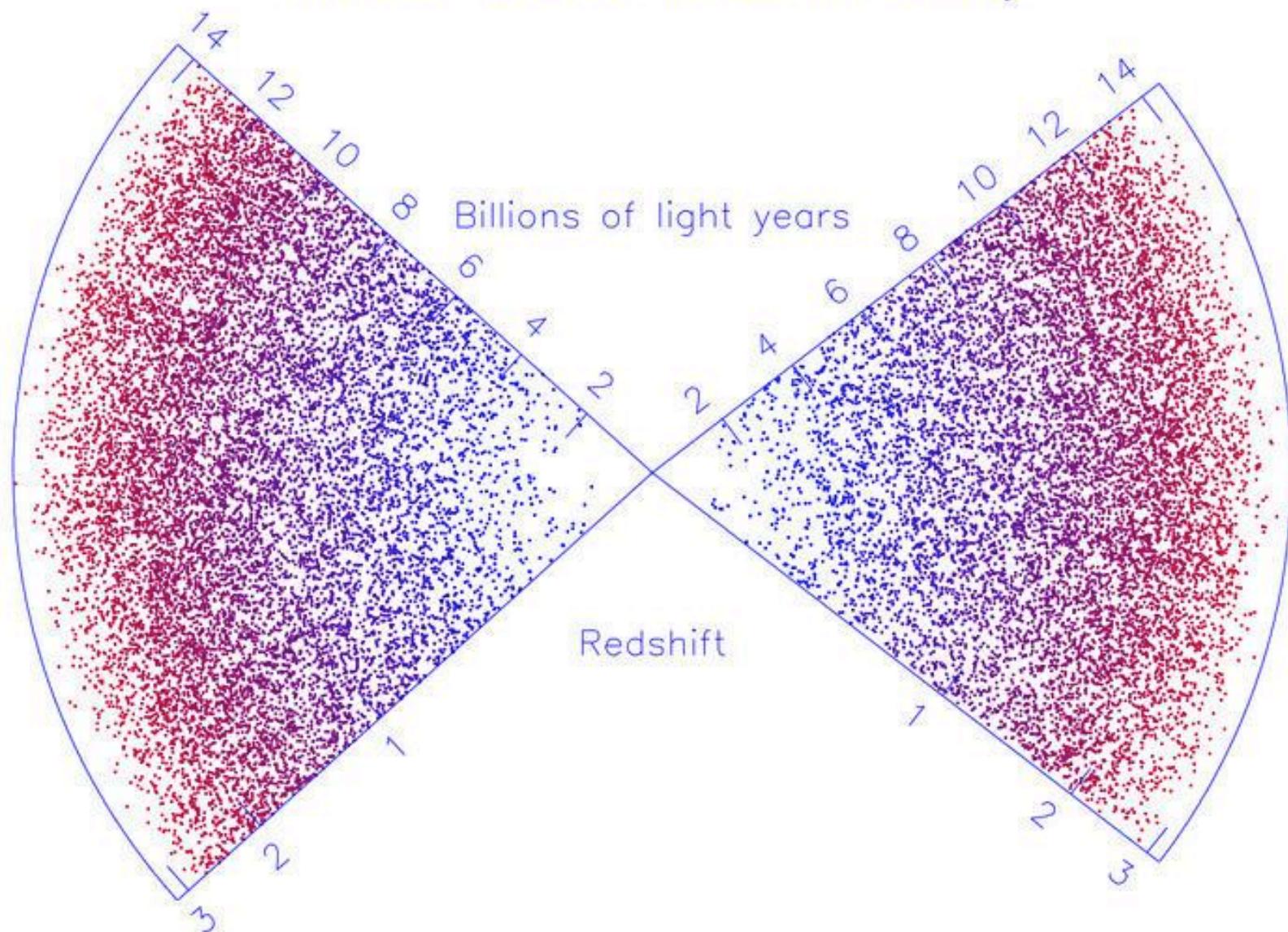
# Ly $\alpha$ Forest: Current Paradigm

- Highly photo-ionized inter- /pre-galactic medium exhibiting coherent filament/wall/void structure induced by the gravitational clustering of cold dark matter, seen in absorption in the spectra of distant quasars
- Repository for most of the baryons in the universe
- Enriched with heavy elements at a low level

# Outline

- Motivation
- Observations
- Simulations
- Theory *post facto*
- The Forest as a Cosmological Probe
  - Parameter studies
  - Complications comparing with data
  - Concordance model at  $z=1.95$
- Outlook

## The 2dF Quasar Redshift Survey



# Motivation

*Why study quasar absorption line systems?*

- Large, unbiased data set which
  - Probes the dark matter distribution over a large range of  $z$  and length scales
  - Encodes the ionization state of the gas and hence history of UV emitting sources
  - Records the metal enrichment of the IGM
  - Remembers the epochs of H I and He II reionization

# Structure of the IGM in $\Lambda$ CDM

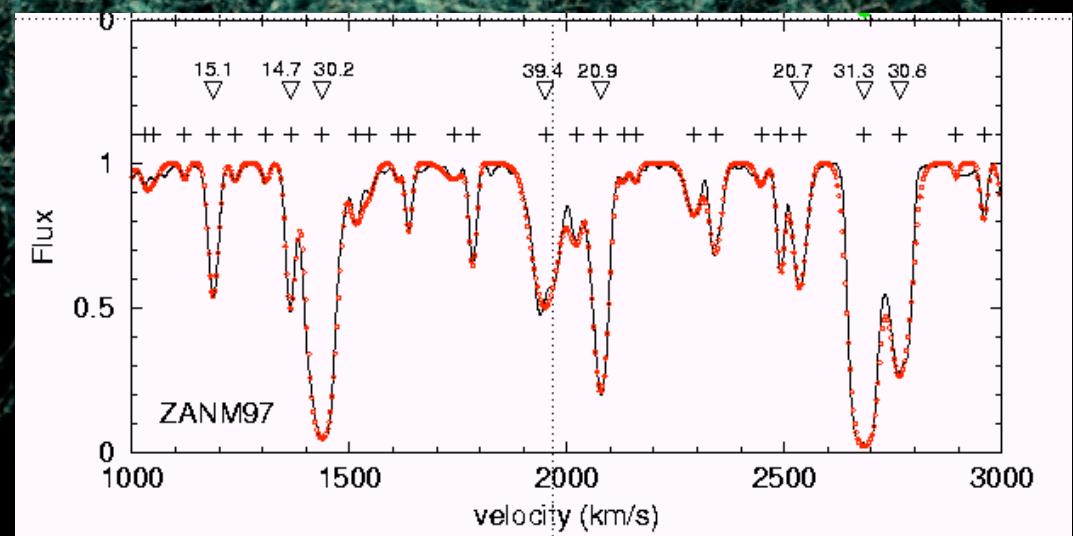
$N=1024^3$

$L=54 \text{ Mpc/h}$

Earth

quasar

Simulated HI absorption spectrum



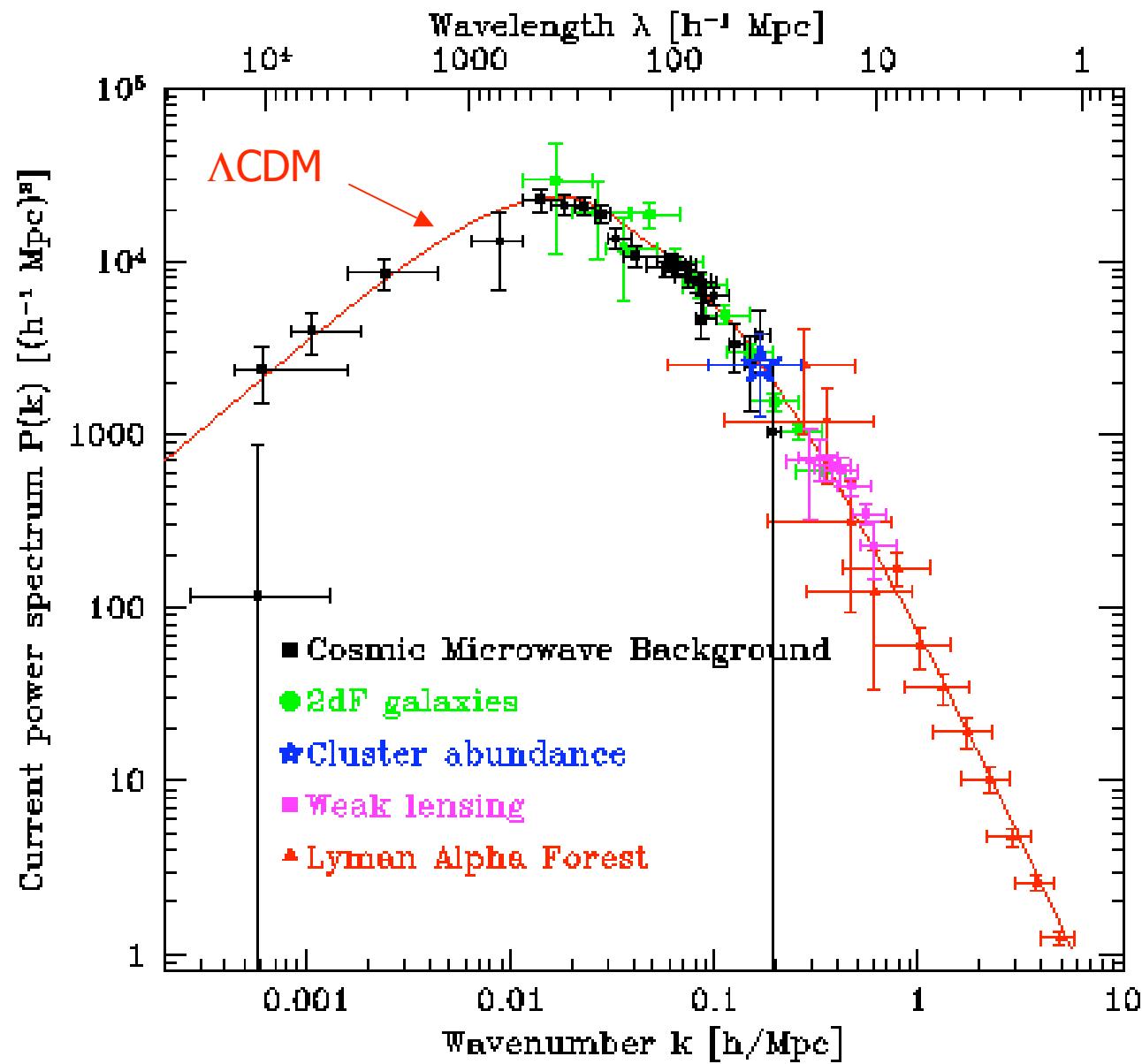
Baryon Overdensity,  $z=3$

Volume: 1024 x 1024 x 1024 | Window: 1024 x 1024

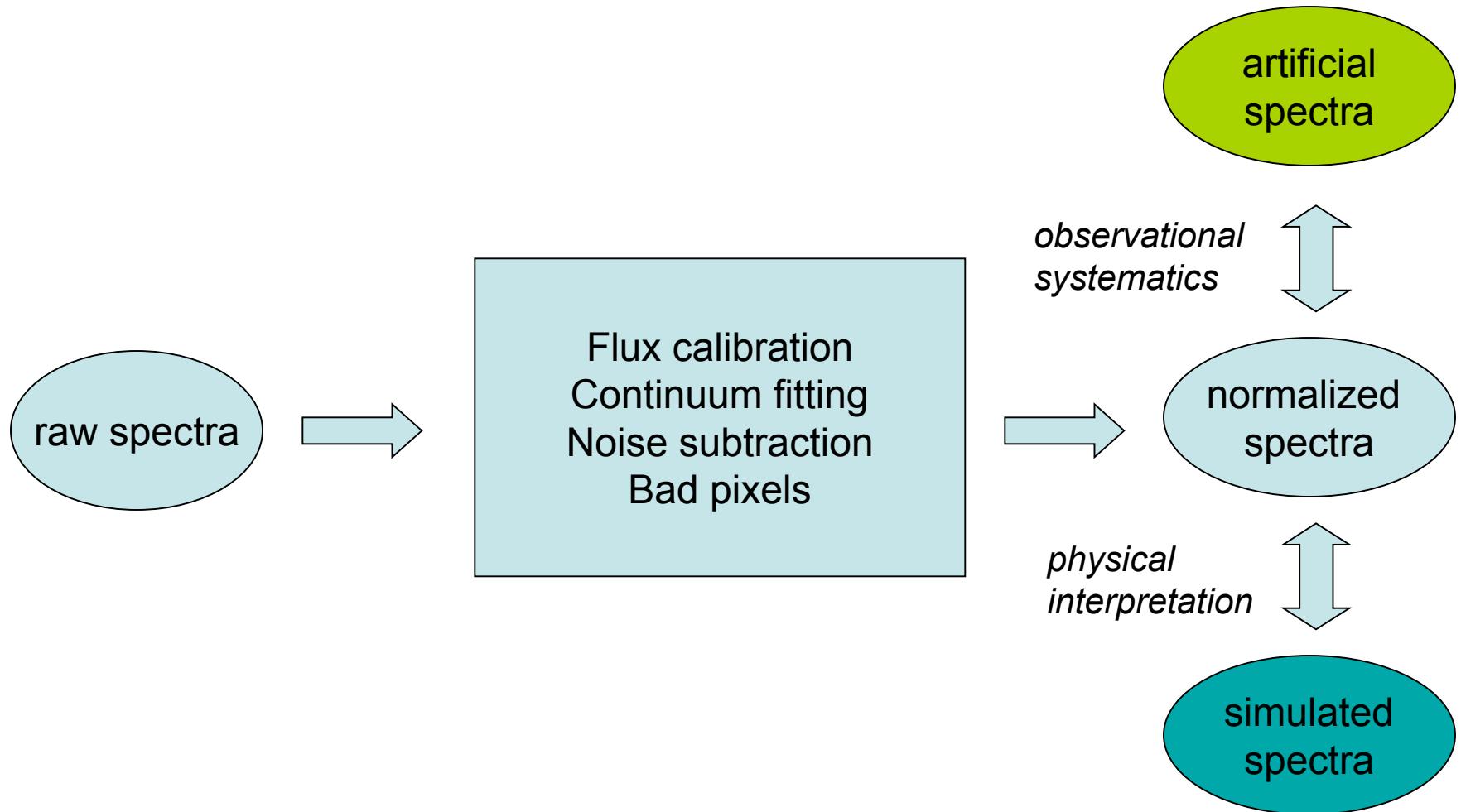
# Precision cosmology using the Lyman $\alpha$ forest

- Absorption spectrum is a 1D map of **neutral hydrogen** along LOS
- Assuming gas is in **ionization equilibrium** with known UV background, have 1D map of **baryons** along LOS
- Baryons closely follow dark matter, hence have 1D map of **total mass density** along LOS
- Many LOS sample **matter power spectrum  $P(k)$**
- Simulations provide **mapping** between absorption spectra and  $P(k)$

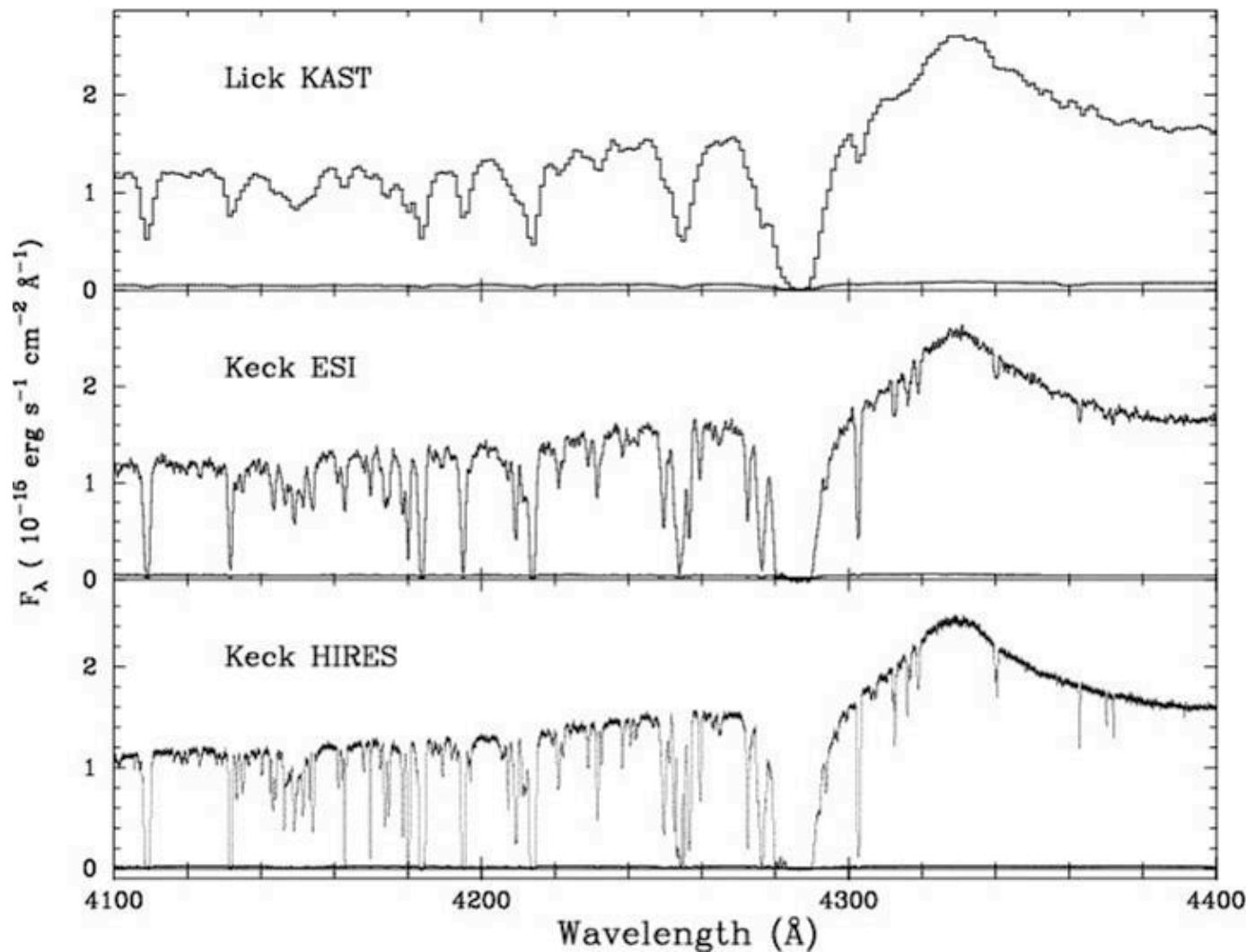
# Matter Power Spectrum $P(k)$



# Observations

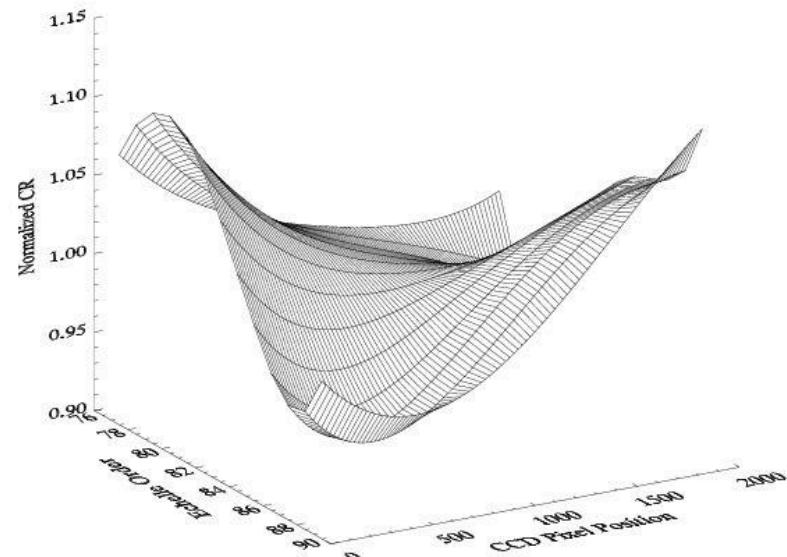
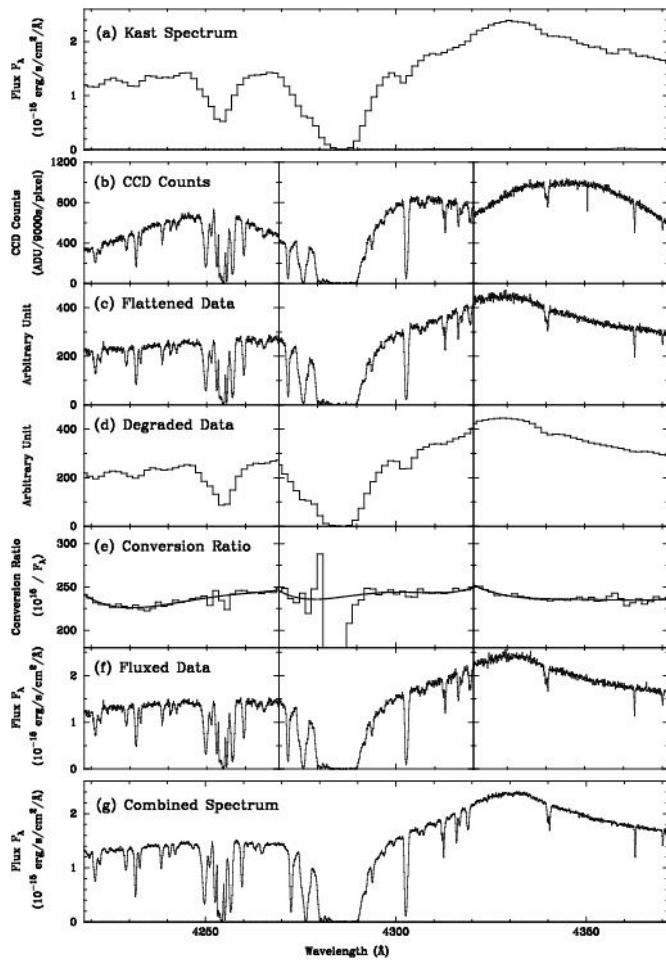


# Ly $\alpha$ Forest and Spectral Resolution

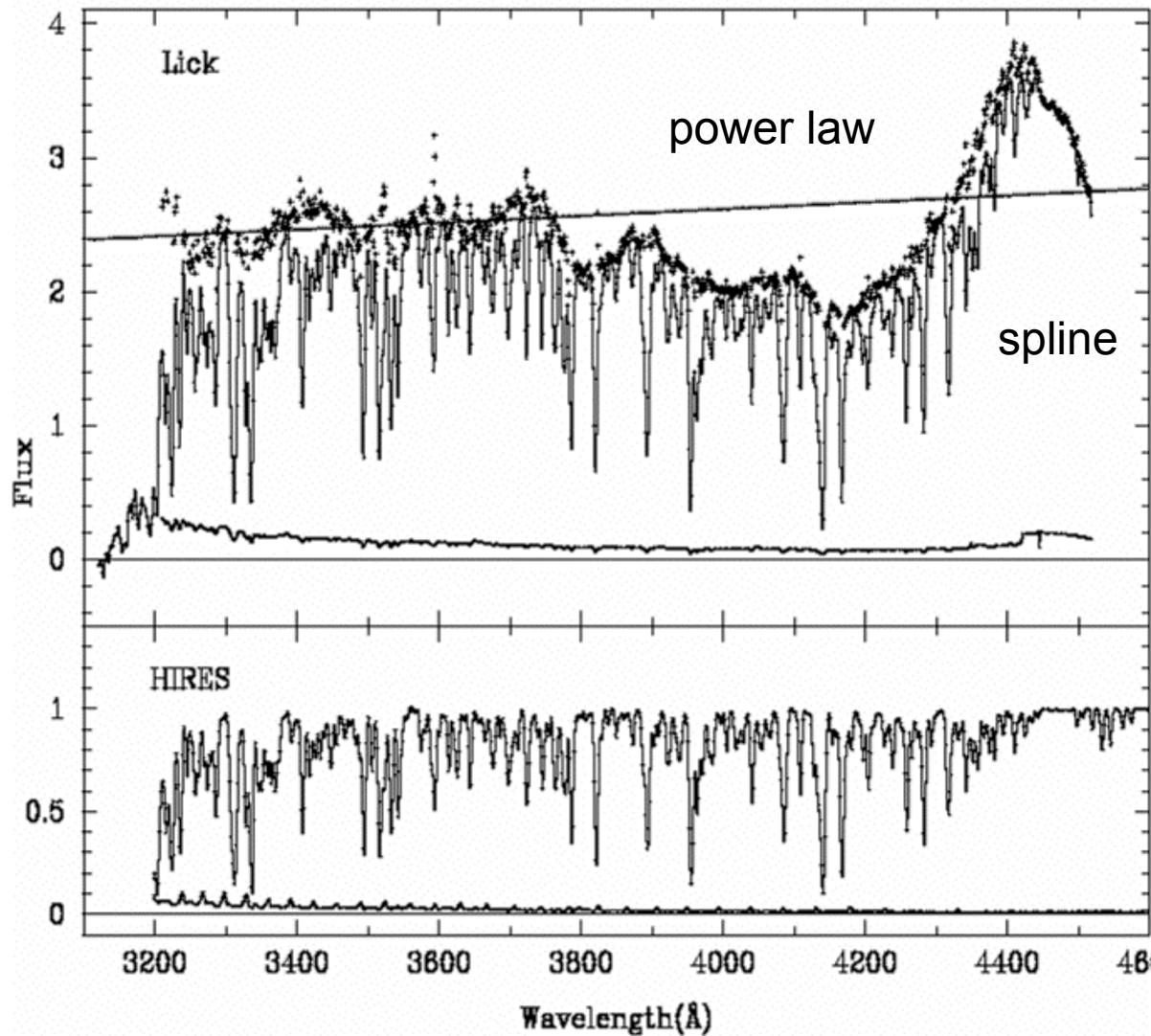


N. Suzuki Ph. D. thesis

# Flux Calibration from the same Quasar Spectrum

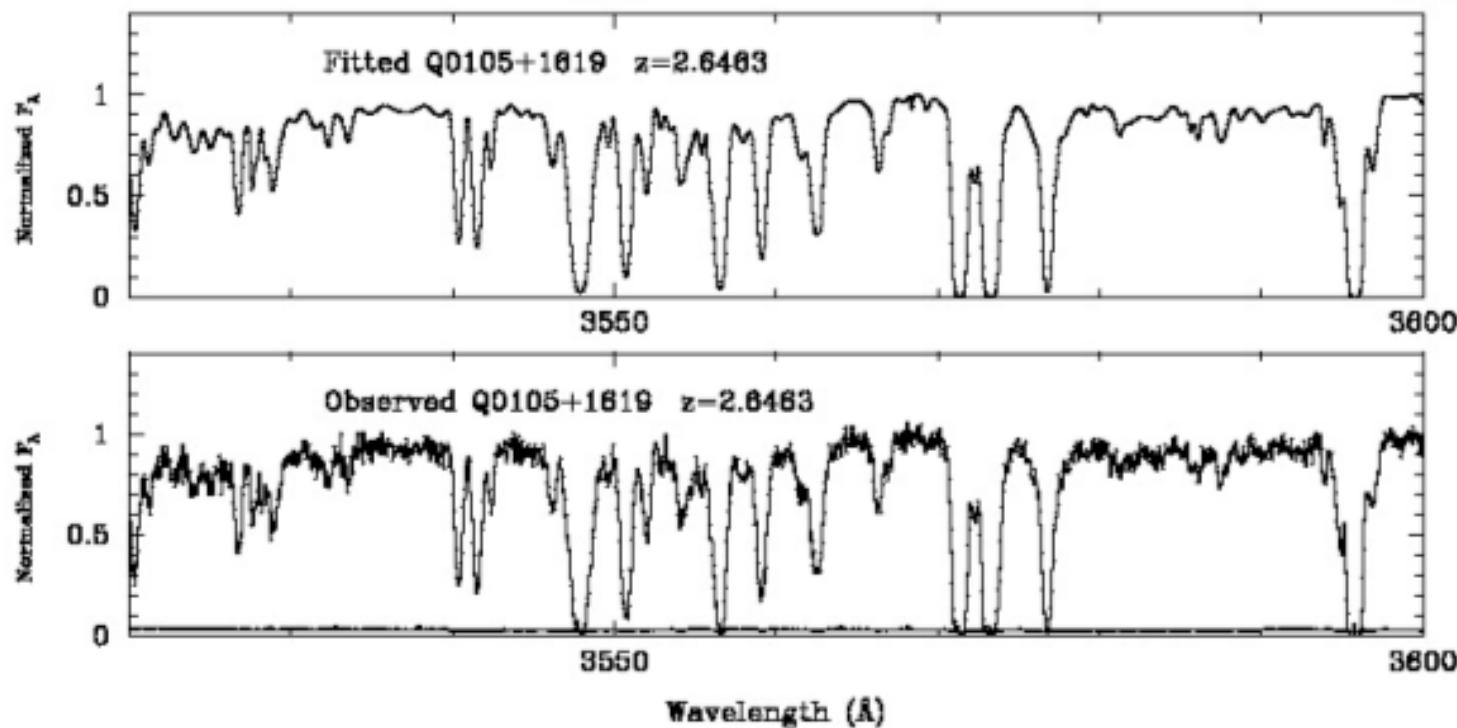


# Continuum Fitting



# Voigt Profile Decomposition

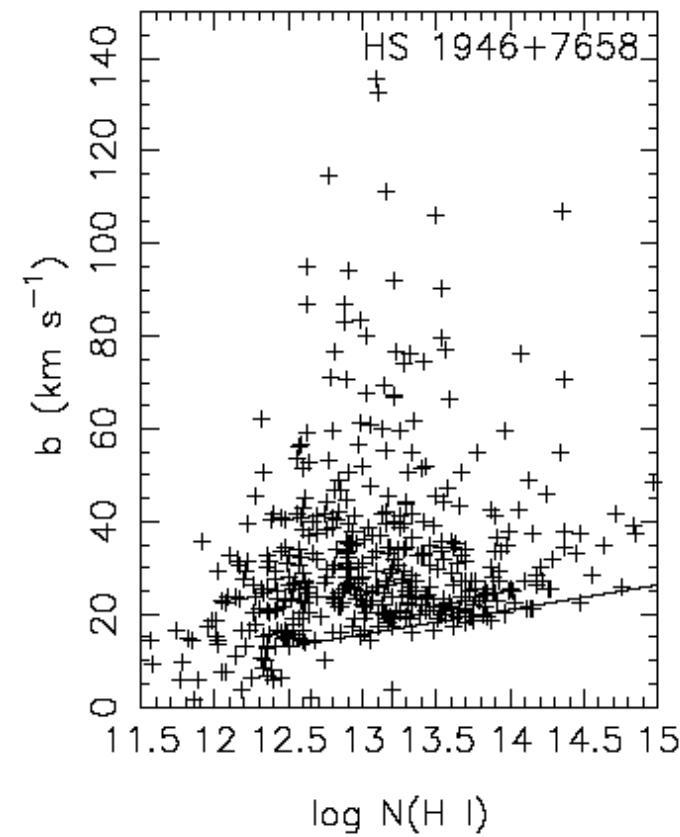
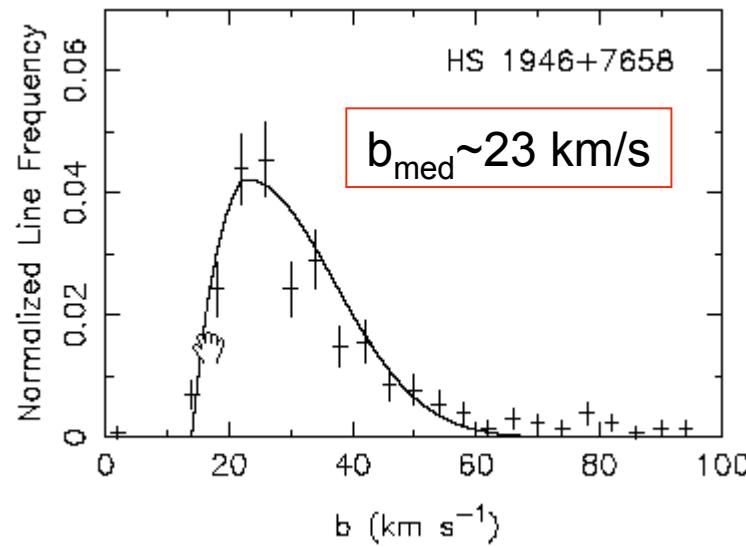
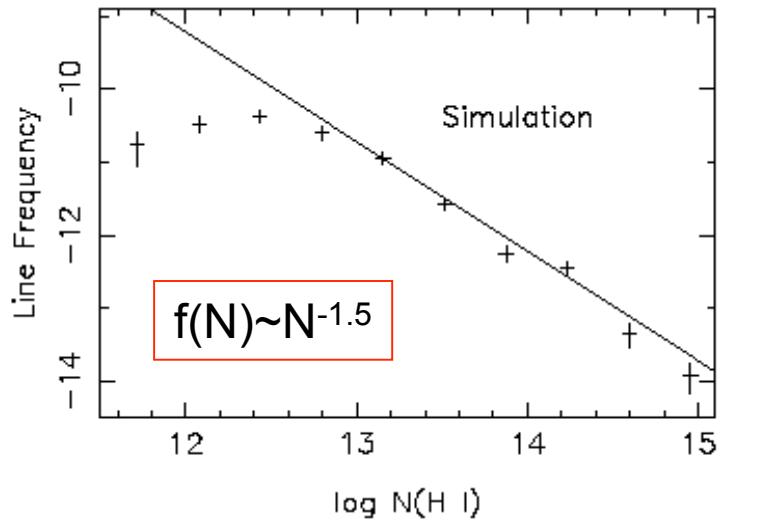
$$F(\lambda) = e^{-\tau(\lambda)}$$
$$\tau(\lambda) = \sum_i VP(N_{HI}, b, \lambda_i)$$



# Analysis of Spectra

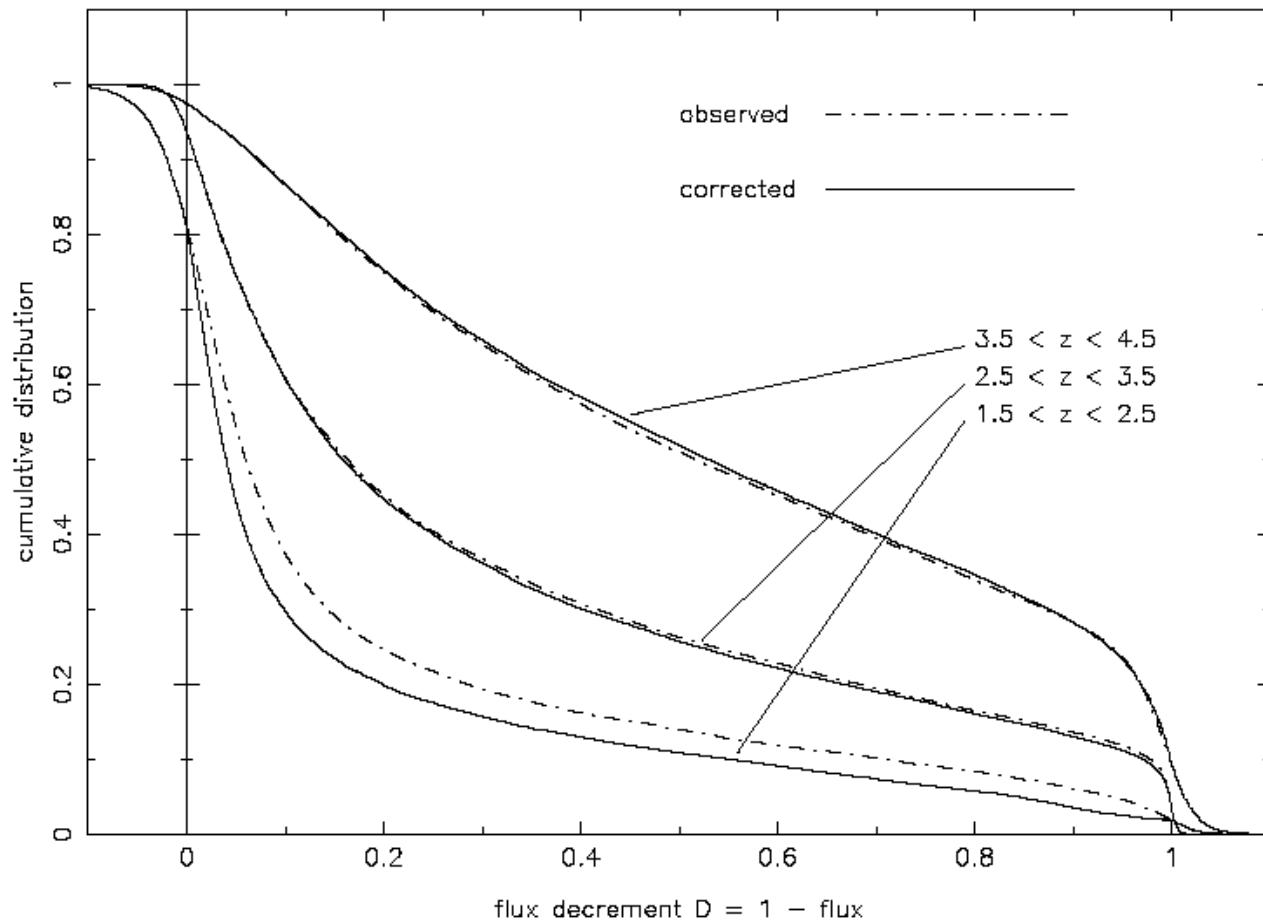
- Line statistics
  - Column density distribution:  $f(N_{\text{HI}}; z)$
  - Linewidth distribution:  $f(b; z)$
  - Column density vs. linewidth scatter:  $N_{\text{HI}}$  vs.  $b$
  - Line number density:  $dN/dz$
- Non-parametric statistics
  - Mean transmitted flux:  $\langle F(\lambda; z) \rangle$
  - Flux-opacity distributions:  $f(F)$ ,  $f(\tau)$
  - Flux power spectrum:  $P_F(k)$

# HS 1946+7658 $\langle z \rangle_{\text{abs}} = 2.72$



Kirkman & Tytler (1997)

# Flux Distribution Function



Rauch et al. (1997)

# Flux Power Spectrum

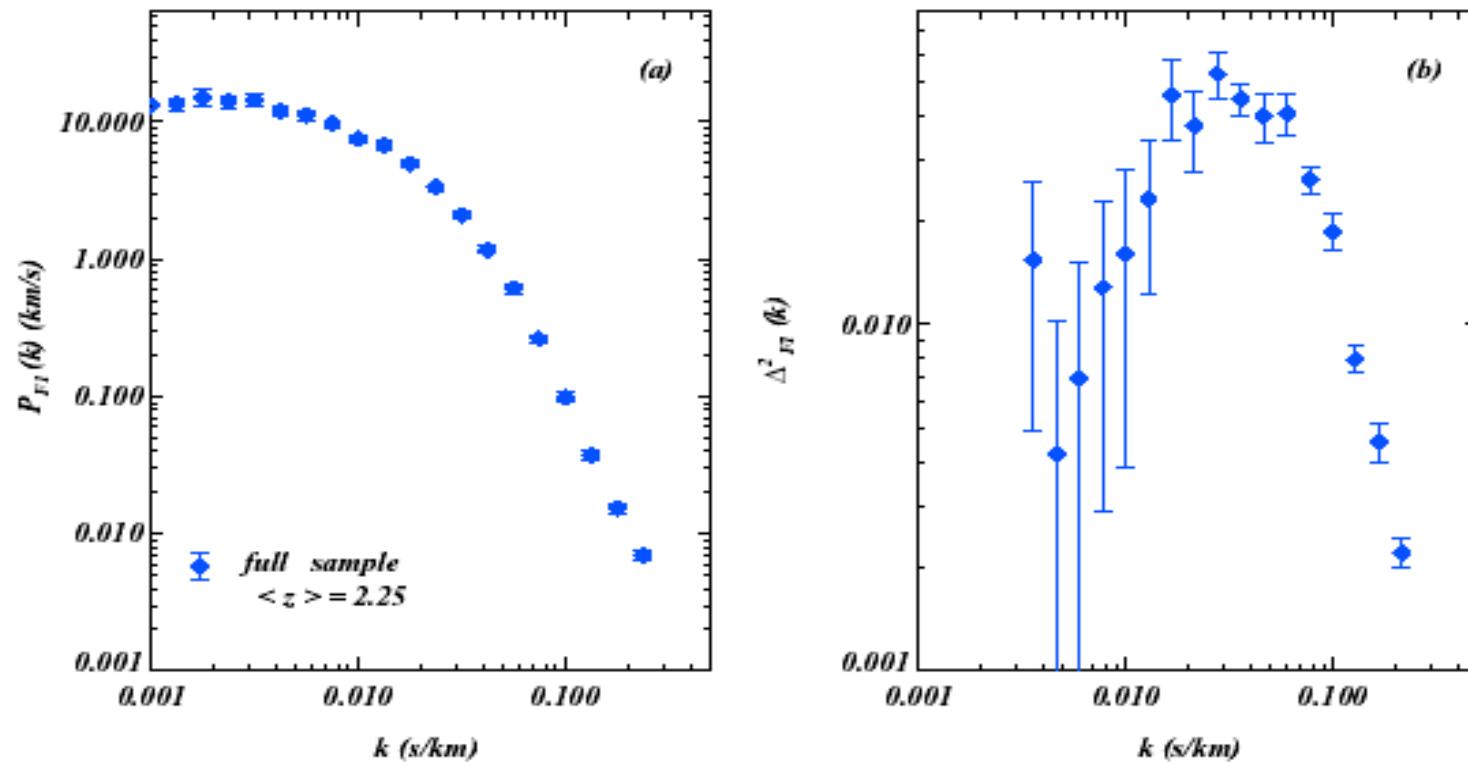
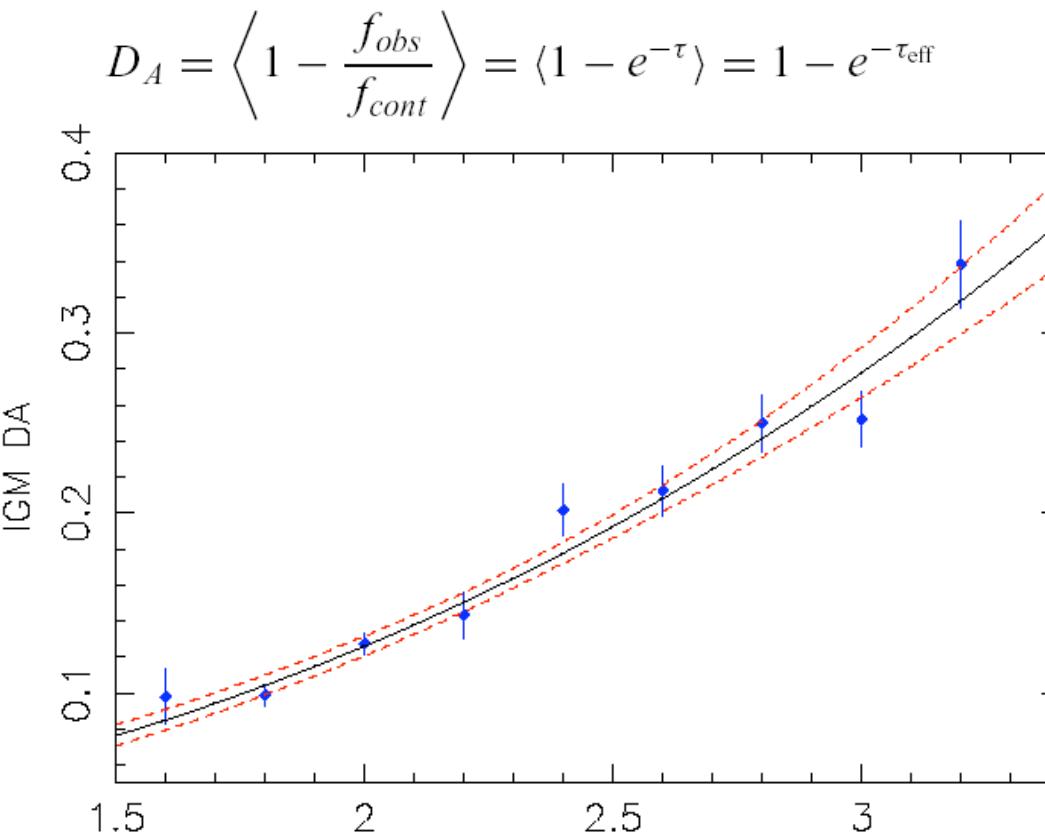


Figure 4. The 1D and “3D” flux power spectrum of the full sample for the flux estimator  $F1 = \exp(-\tau)$ . Errors bars are jackknife estimates. Note that the LUQAS points (diamonds) in the left panel are different from the one in the published version in Kim et al. (2004) MNRAS 347, 355 (where the  $k$  values of the 1D flux power spectrum had been erroneously shifted by half a bin size in  $\log k$ ).

Kim et al. (2004)

# Flux Decrement $D_A$



**Figure 5.** DA as a function of redshift. Here we have binned the data points shown in Fig. 4 into bins of  $\Delta z = 0.2$ . The solid line shows the minimum  $\chi^2$  fit of the function  $A (1+z)^\gamma$ . We find  $A = 0.0062$  and  $\gamma = 2.75$  give  $\chi^2 = 8.69$  for seven degrees of freedom. The dashed lines show the  $\pm 1 \sigma$  confidence interval on the fit.

Kirkman et al. (2005)

# Simulations

- Types of simulations
- Fully hydrodynamic simulations
  - The standard model
  - Inputs and outputs
  - Spectrum synthesis and analysis
- Generic Results
  - Physical Nature of the Ly $\alpha$  forest
  - Correlations
  - Anatomy of an absorber
  - Resolution issues

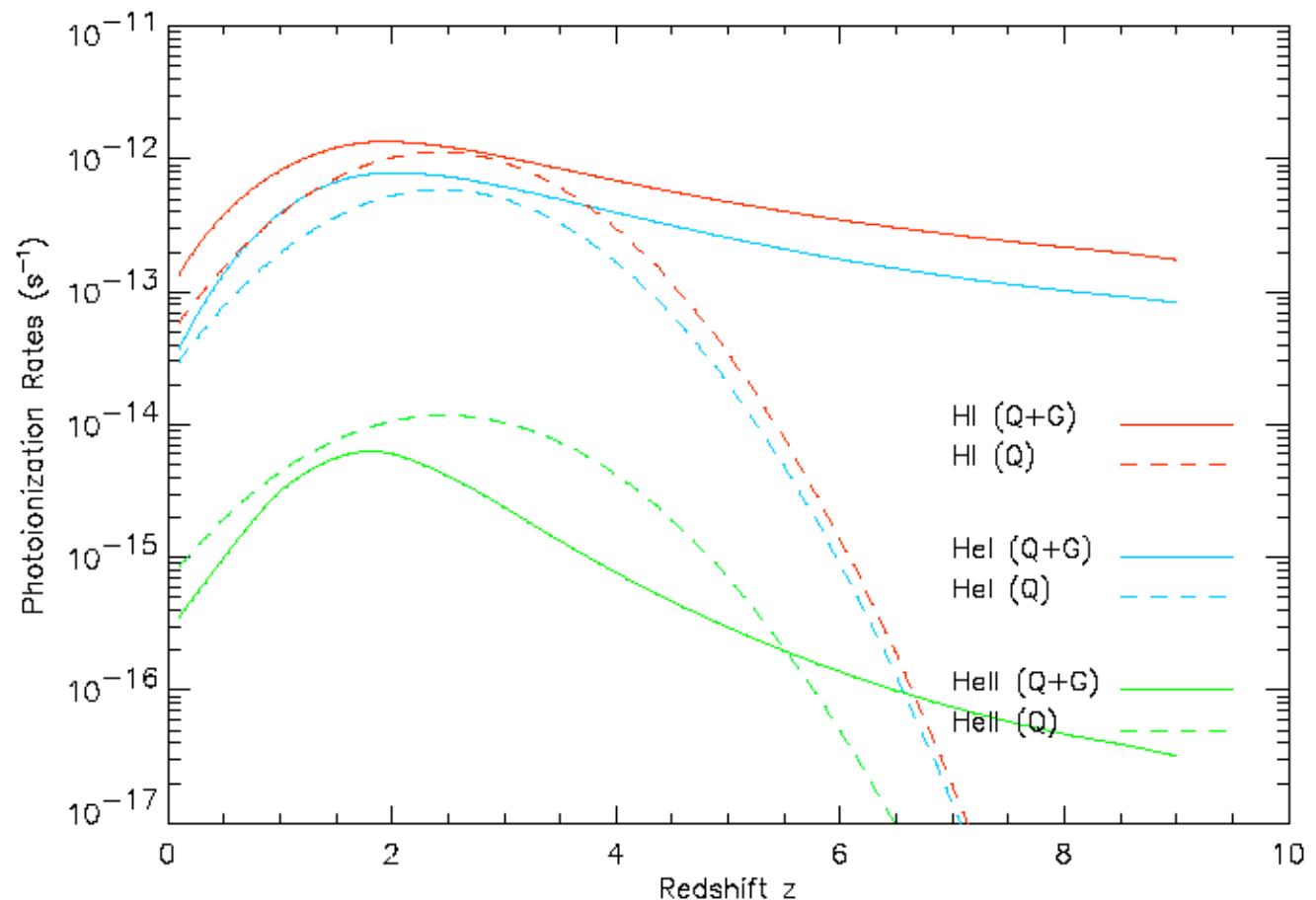
# Types of Simulations

- Fully hydrodynamic
  - SPH Lagrangian: better resolution at high overdensities
  - Eulerian unigrid: better resolution at low overdensities
  - Eulerian AMR: best of both worlds
- Hydro-PM
  - Collisionless PM; gas simulated with modified force law
- Pseudo-hydro
  - Collisionless PM; gas modeled in post-processing

# Fully Hydrodynamic

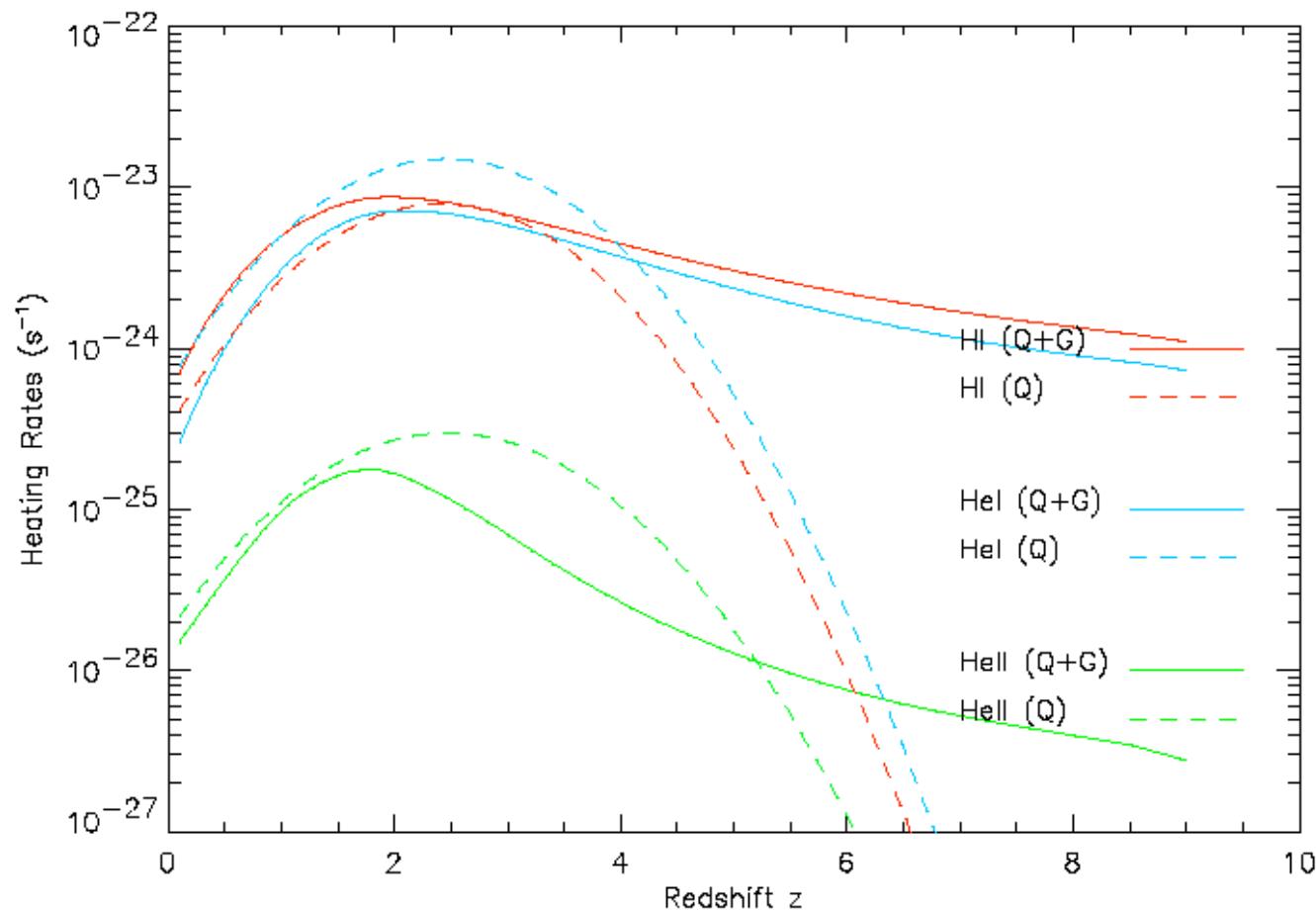
- The standard model
  - Cosmological framework
  - Dark matter (cold or warm)
  - Ideal gas dynamics
  - Self-gravity
  - Primordial gas ionization, heating, and cooling
    - Equilibrium (Katz, Weinberg & Hernquist 1996)
    - Non-equilibrium (Anninos, MN et al. 1997)
  - Metagalactic UV background (optically thin)
    - Quasars only (Haardt & Madau 1996)
    - Quasars + galaxies (Madau, Haardt & Rees 1999)

# Photo-ionization rates



Paschos & Norman (2005)

# Photo-heating rates



Paschos & Norman (2005)

# Fully hydrodynamic

- Not included in standard model
  - Local sources of radiation (inhomogeneities in UV background)
  - Local sources of heating and heavy elements (galactic superwinds)
  - Magnetic fields and cosmic rays
  - Opacity effects (shadowing, self-shielding)
  - Inhomogeneous reionization of He II by QSOs (late heating)

# $\text{Ly}\alpha$ Forest Simulation

$L$  (box) = 19.2 Mpc (comoving)

Resolution Elements =  $256^3$

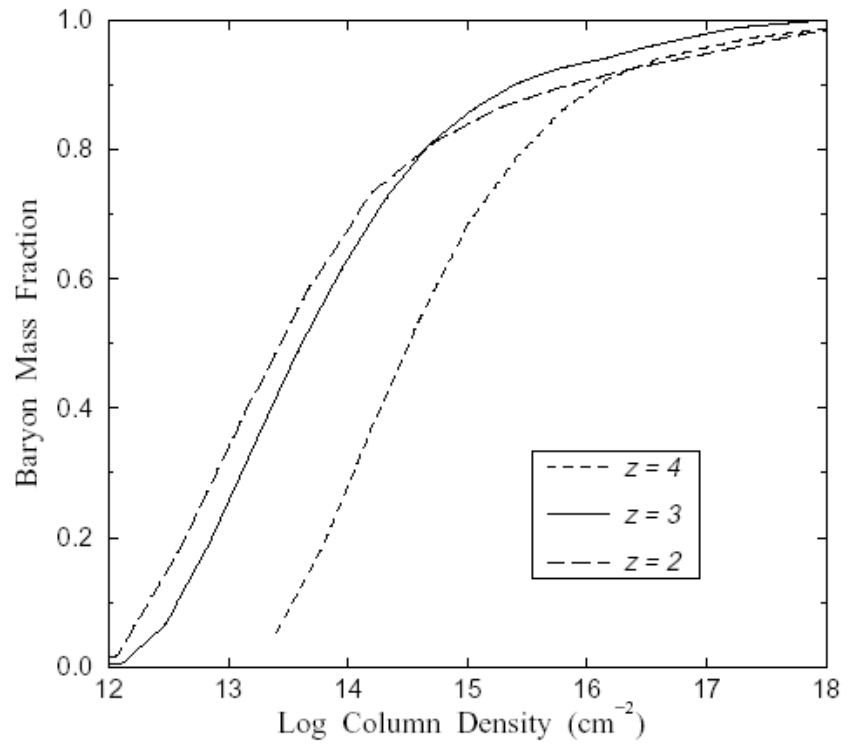
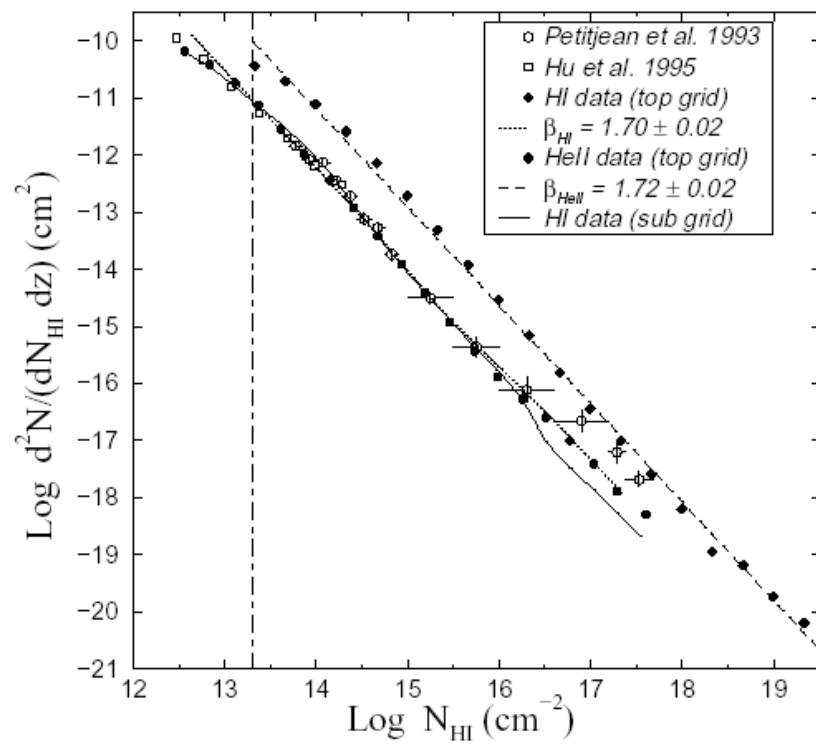
Field =  $\log(\rho_{\text{HI}} / \rho_{\text{B}})$

Redshifts : 60 - 2.0



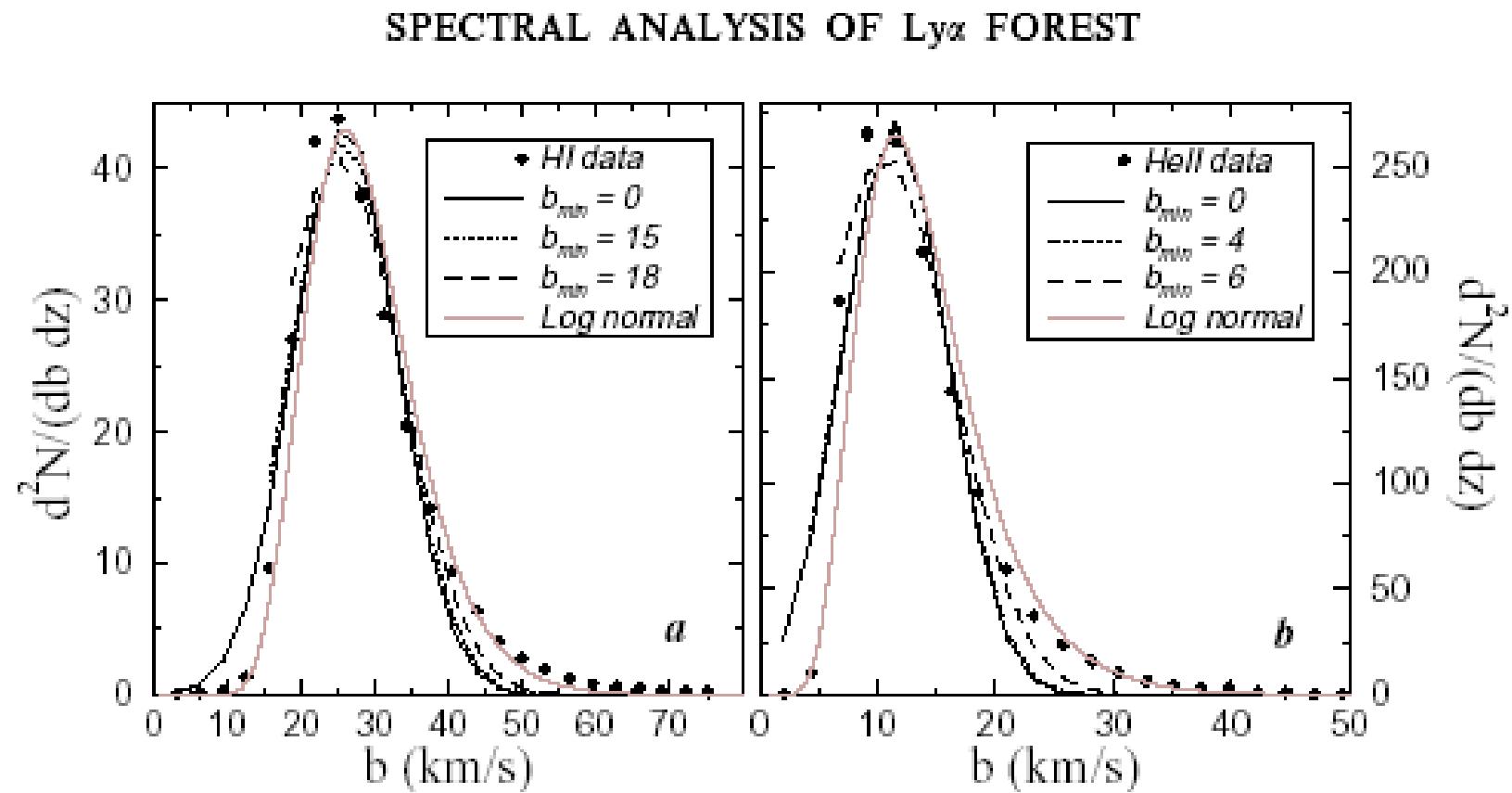
Wen Ching Lin, 2001

# Column Density Distribution & Cumulative Baryon Fraction



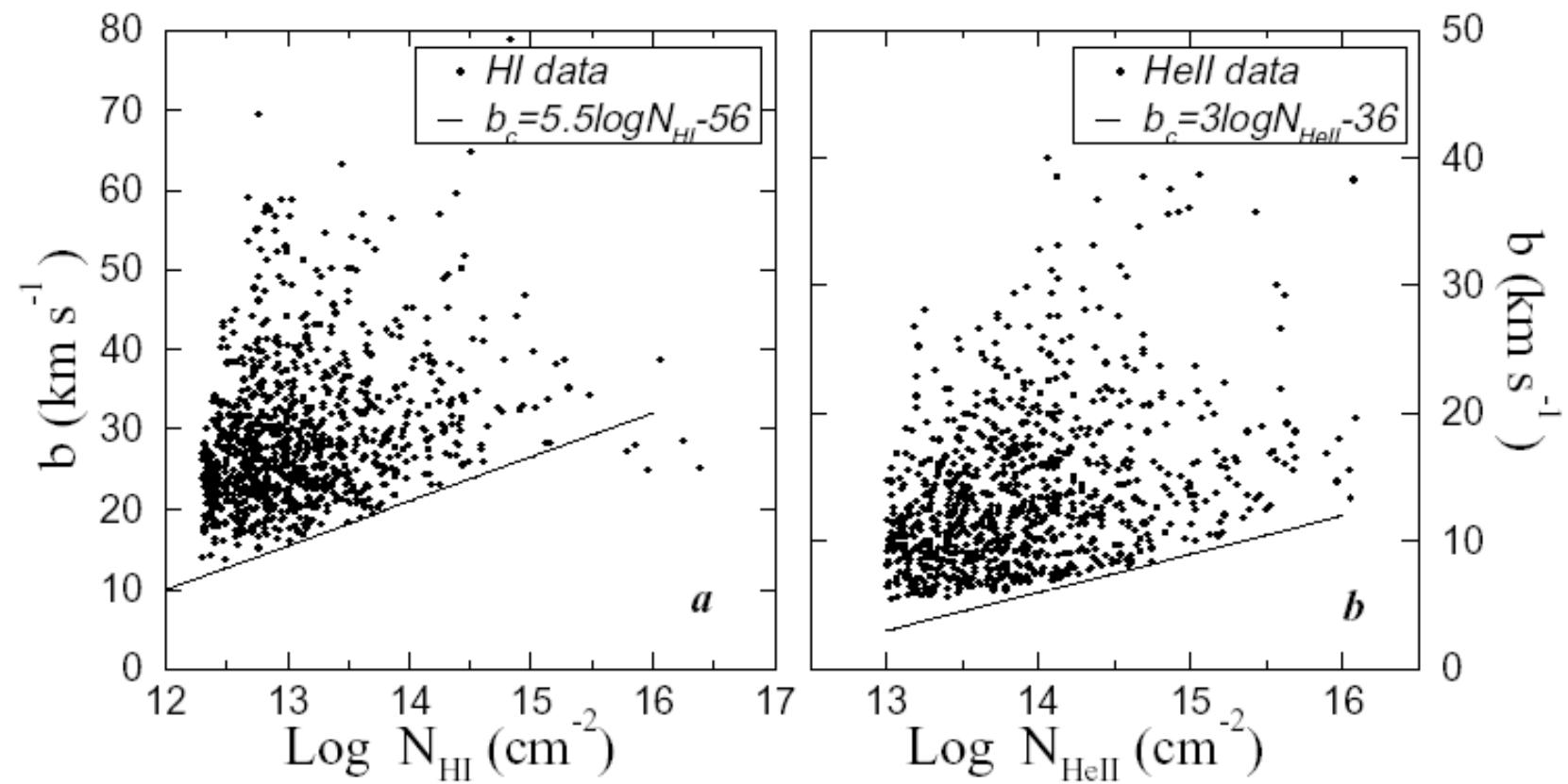
Zhang et al. (1997, 1998)

# Doppler Parameter Distribution



Zhang et al. (1997)

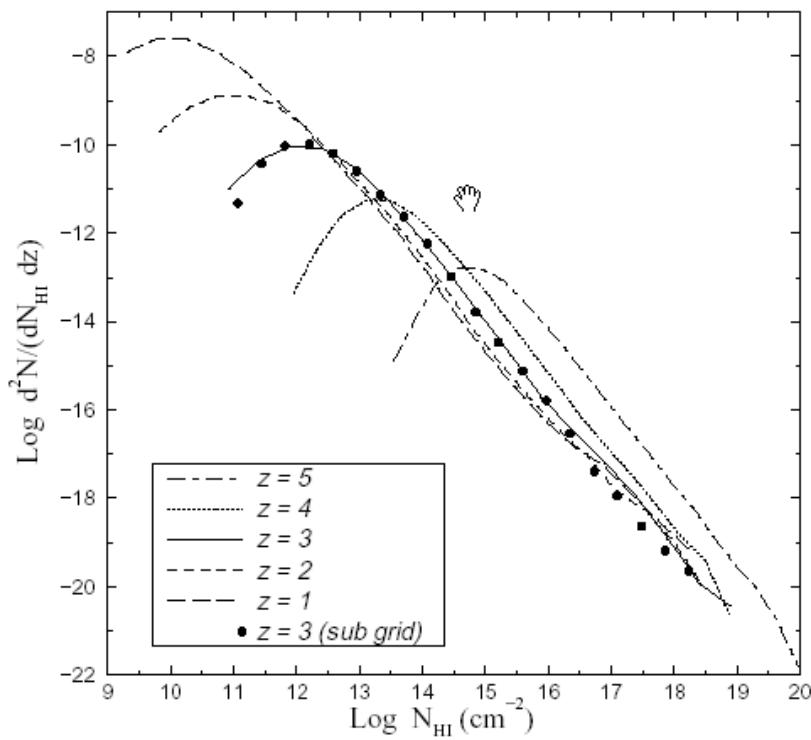
# b vs. N



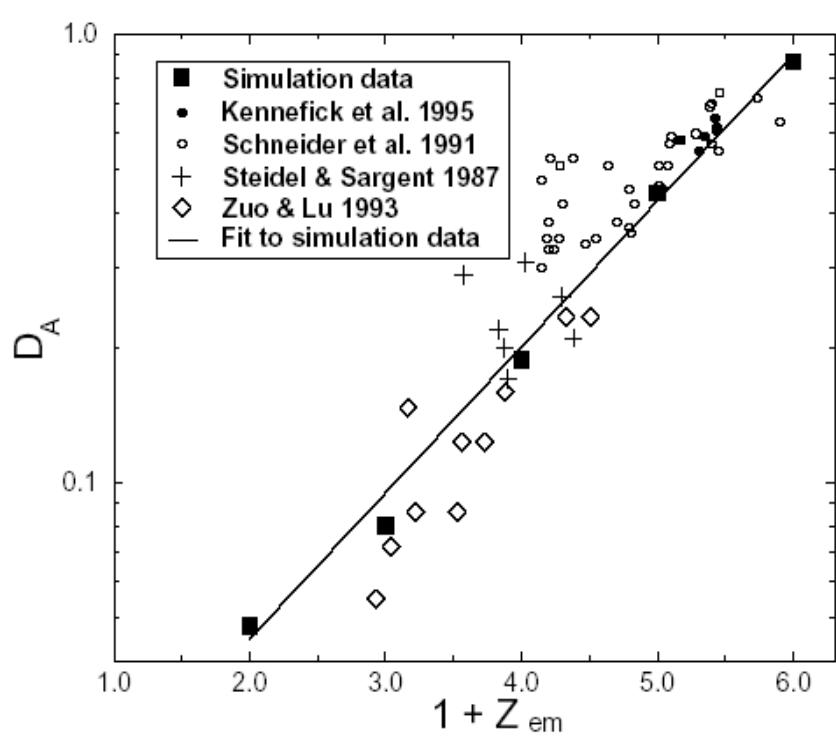
Zhang et al. (1997)

# Evolution

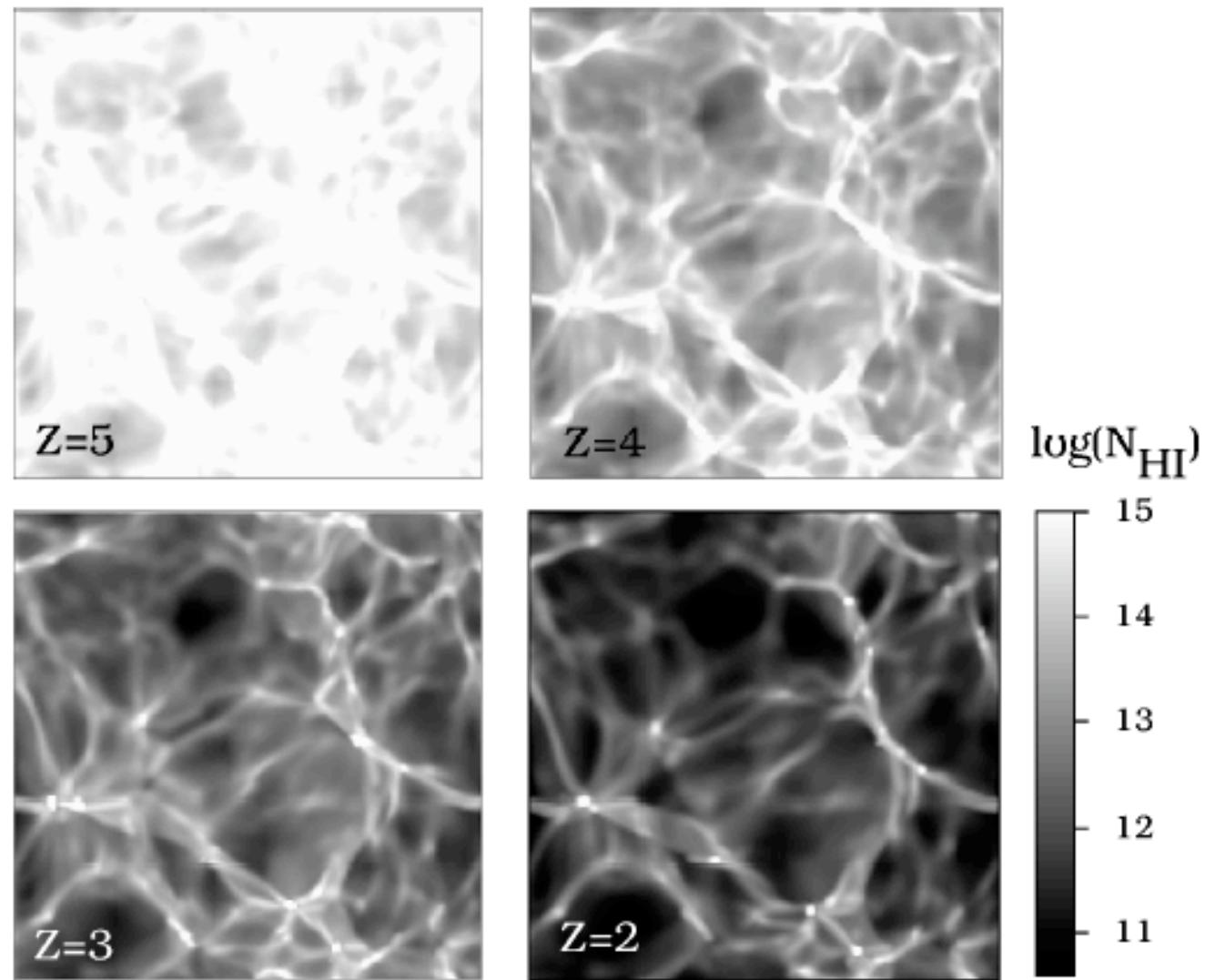
$f(N_{\text{HI}}; z)$



$D_A$



Zhang et al. (1997)

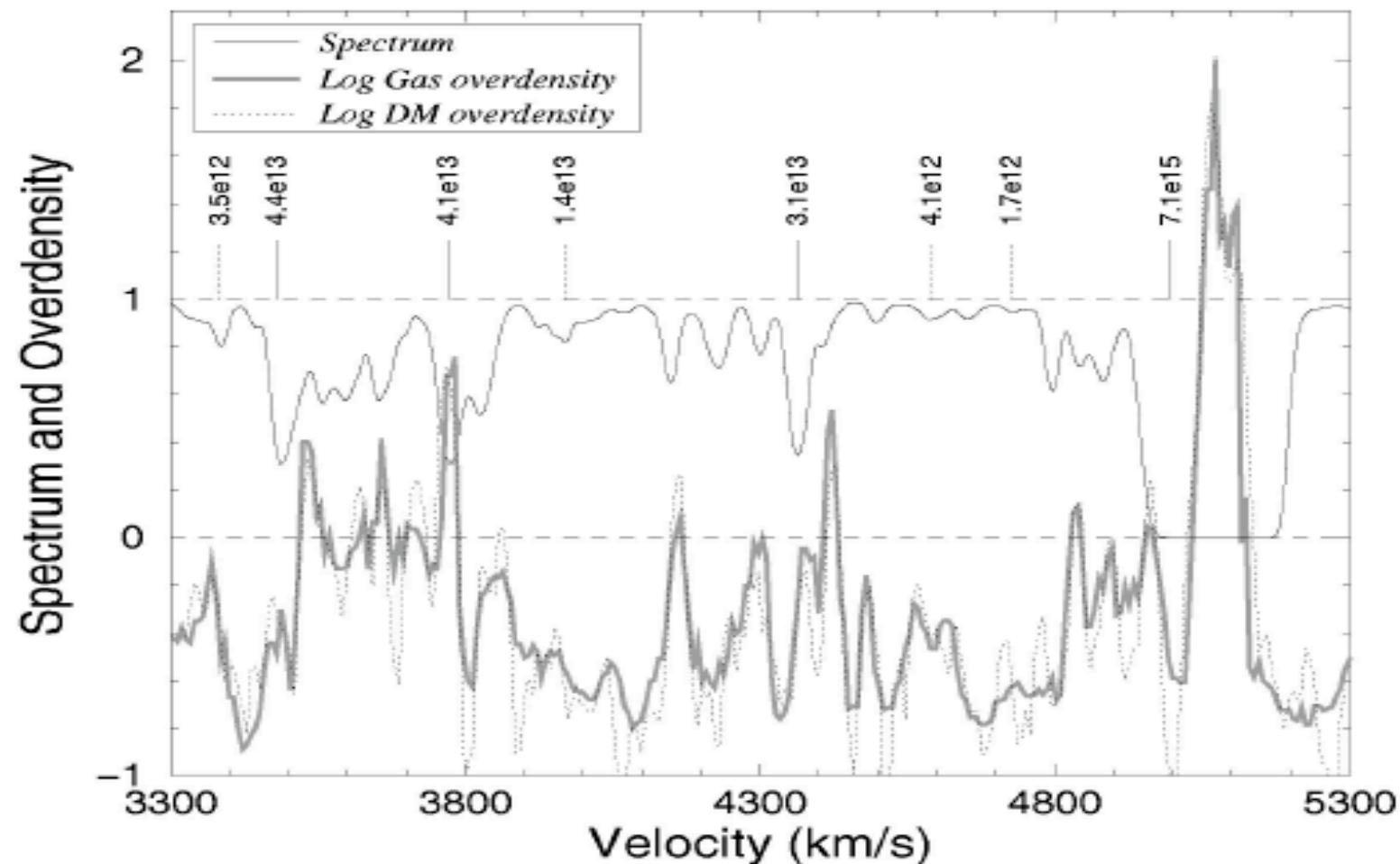


Zhang et al. (1998)

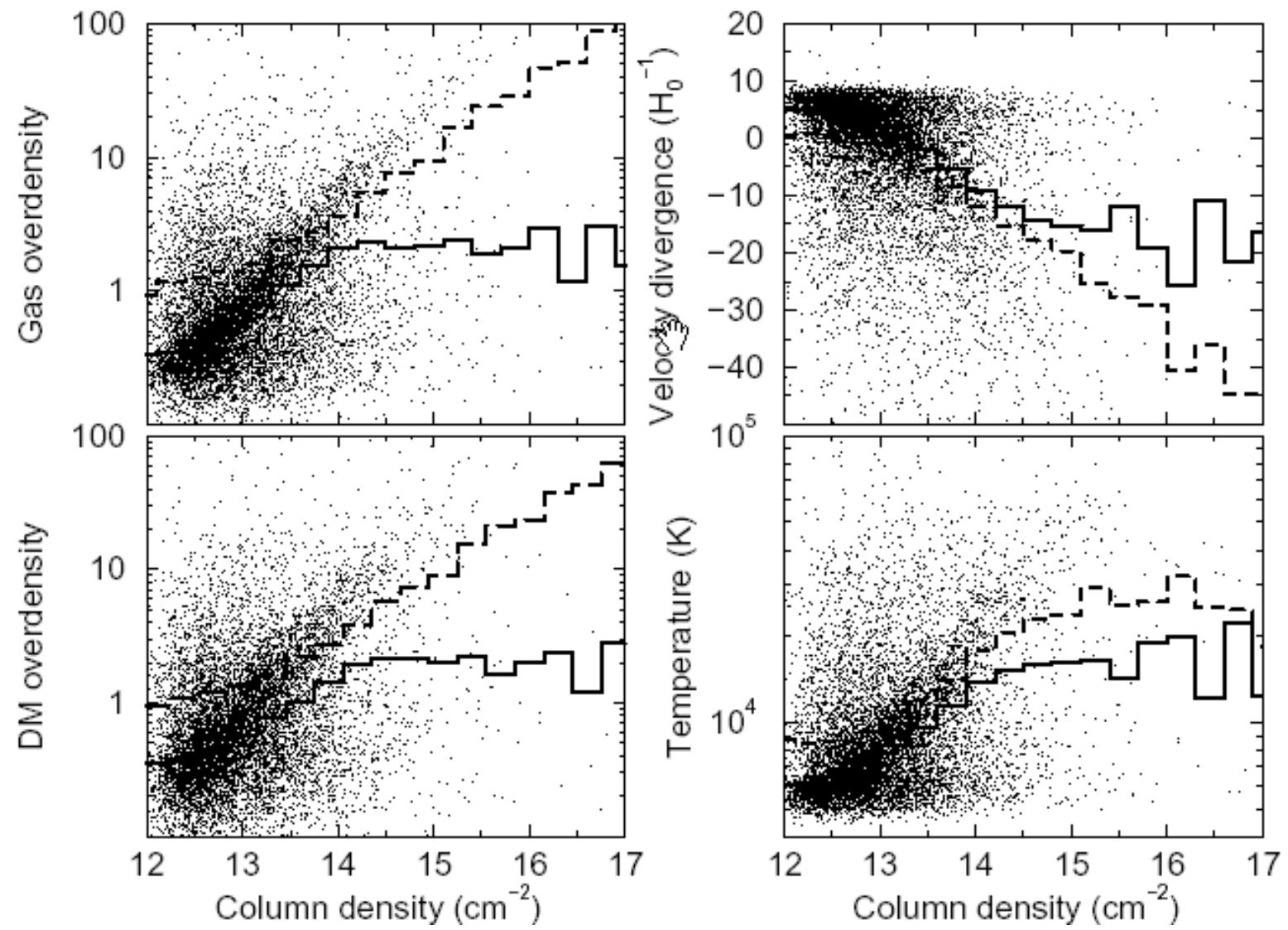
A wide-angle photograph of a sunset over a calm body of water. The sky is filled with intense orange and red hues. A massive, dark plume of smoke and fire rises from the horizon, billowing upwards and to the left. The silhouette of distant mountains is visible against the bright sky.

**INTERMISSION**

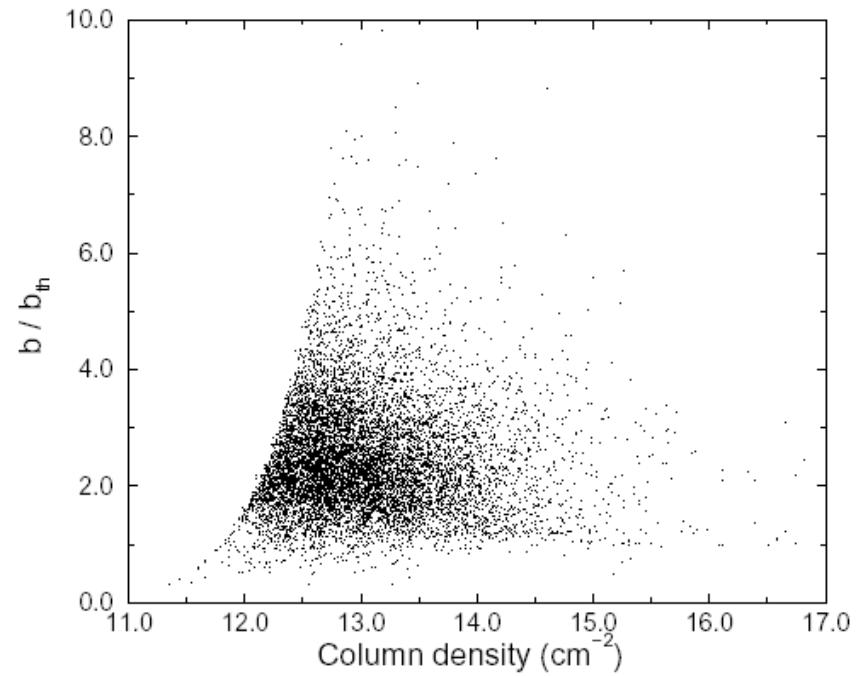
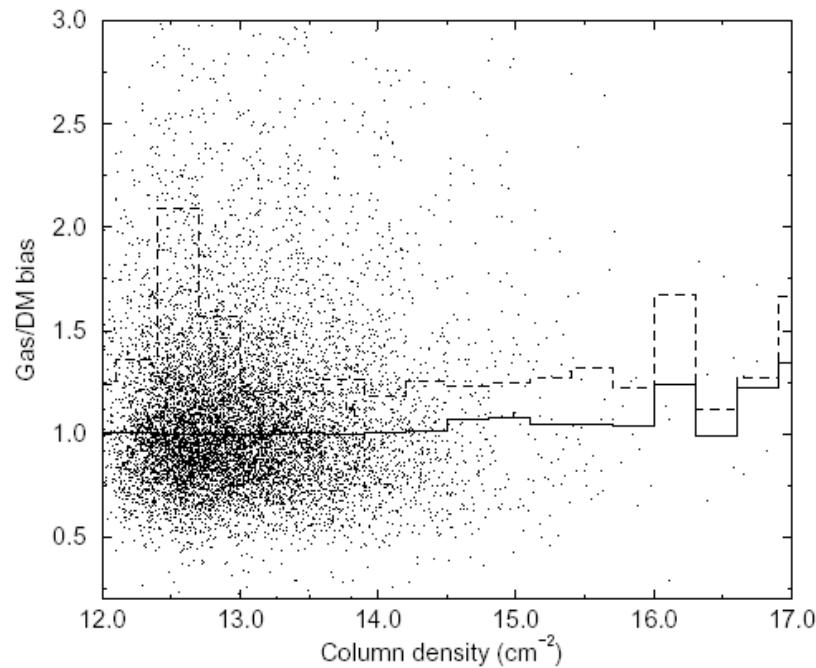
# Correlation of Spectral Features



Zhang et al. (1998)

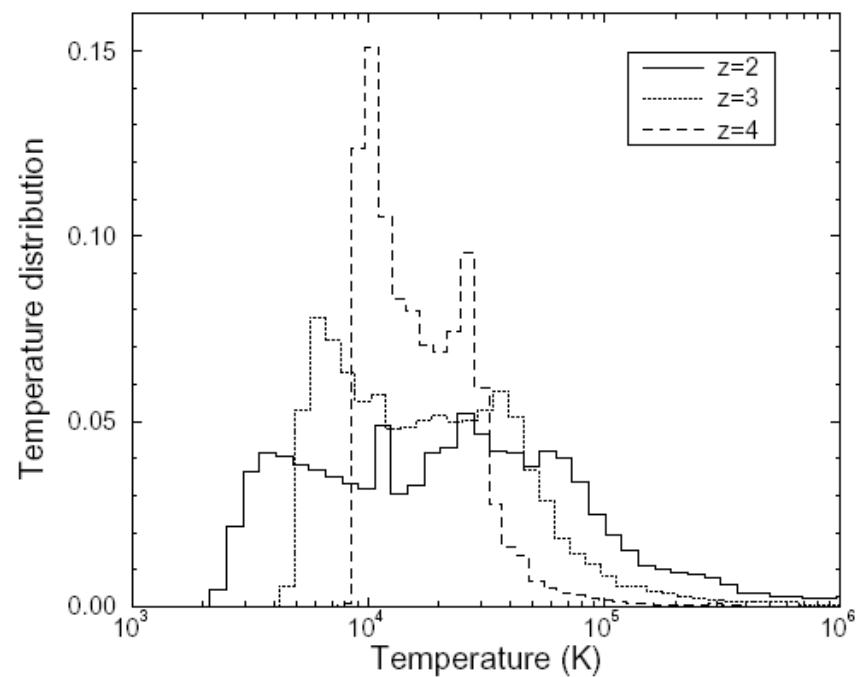
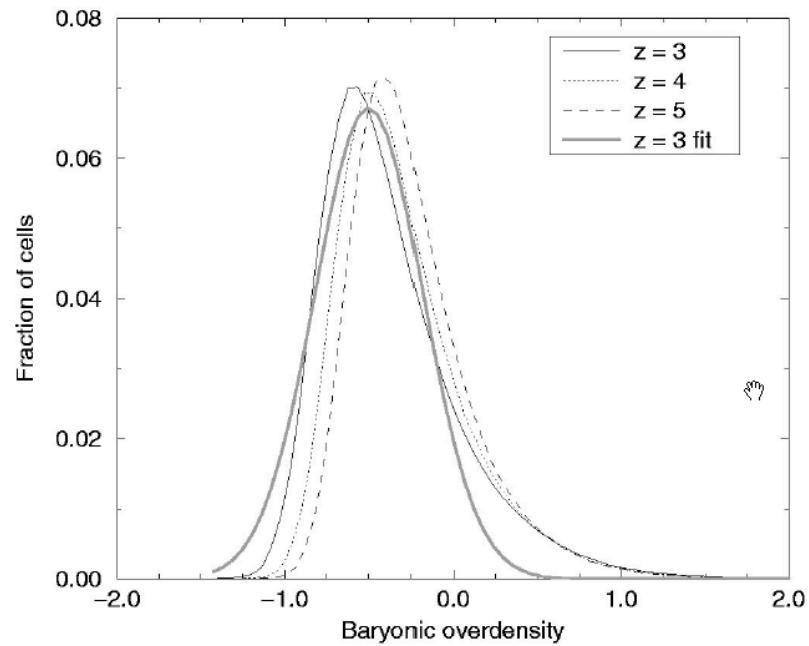


# Biases



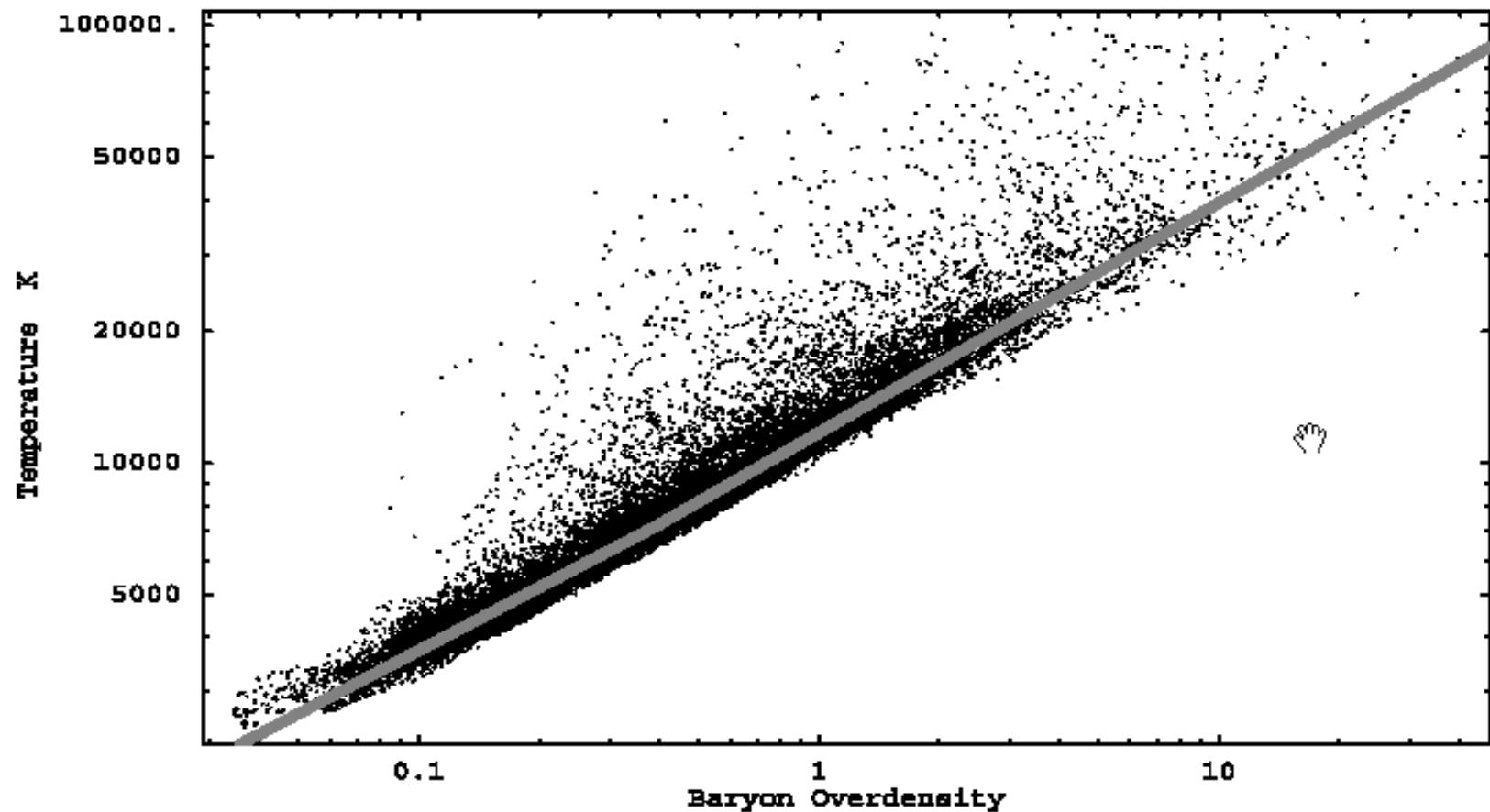
Zhang et al. (1998)

# Temperature, Density DF



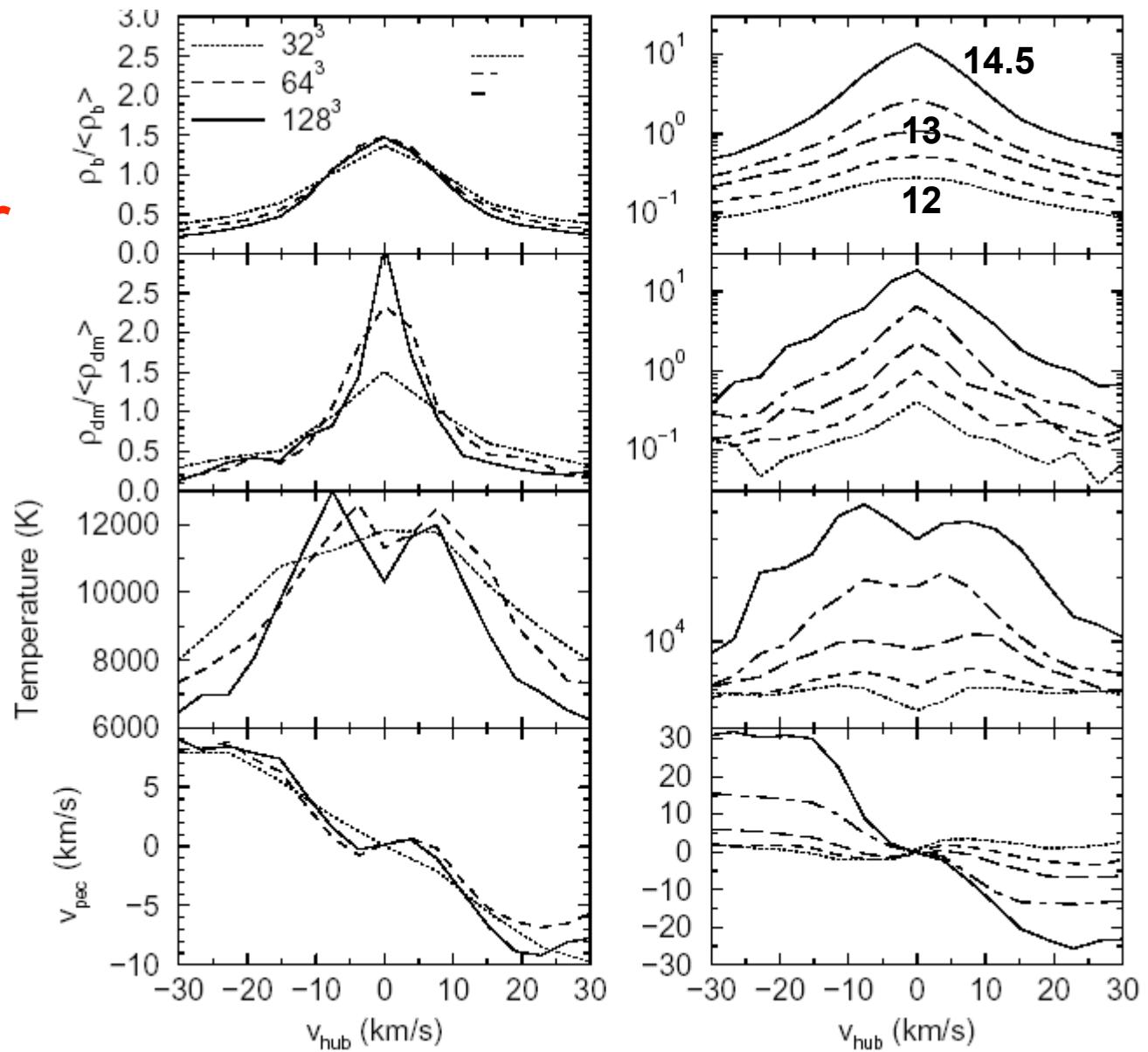
Zhang et al. (1998)

# EOS of IGM?



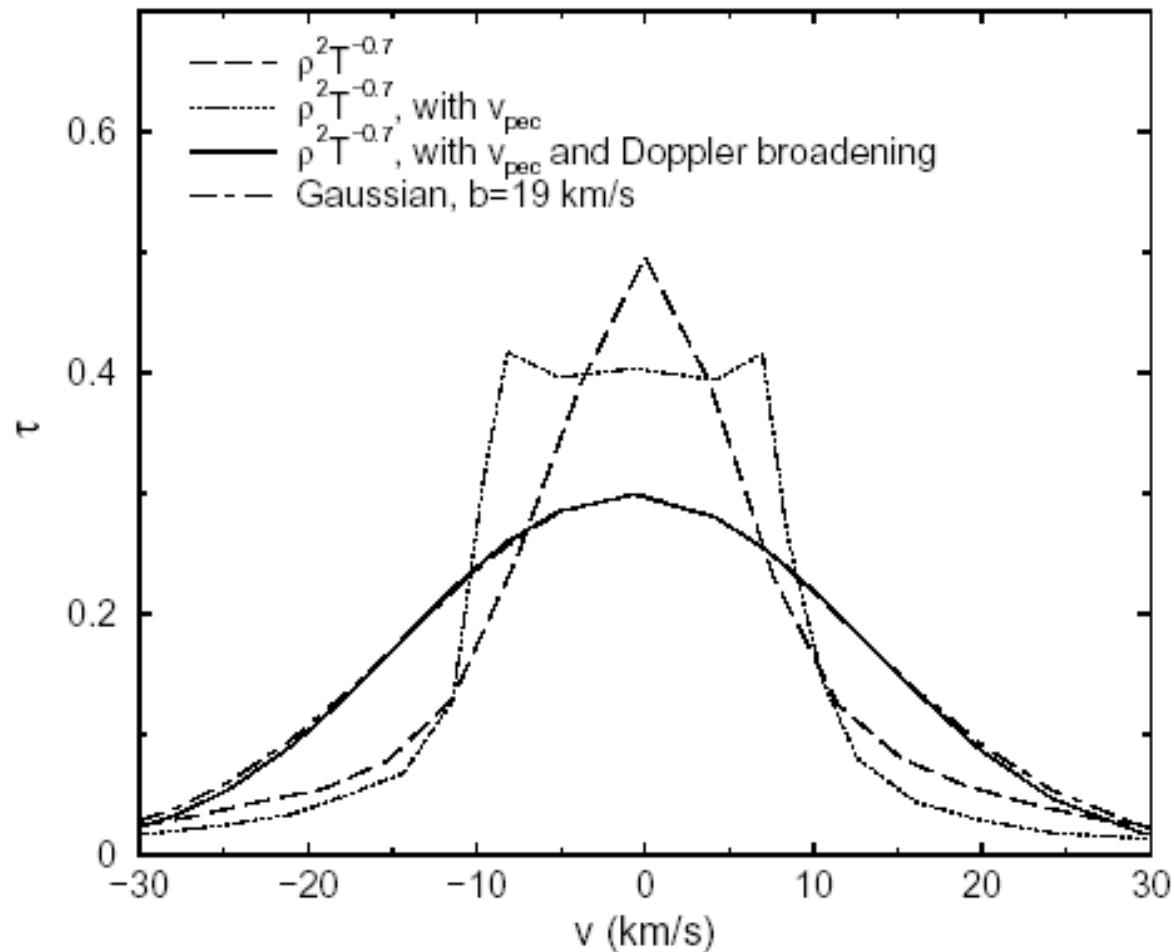
Tytler et al. (2004)

# Anatomy of an Absorber



Bryan et al. (1999)

# Contributions to $b$



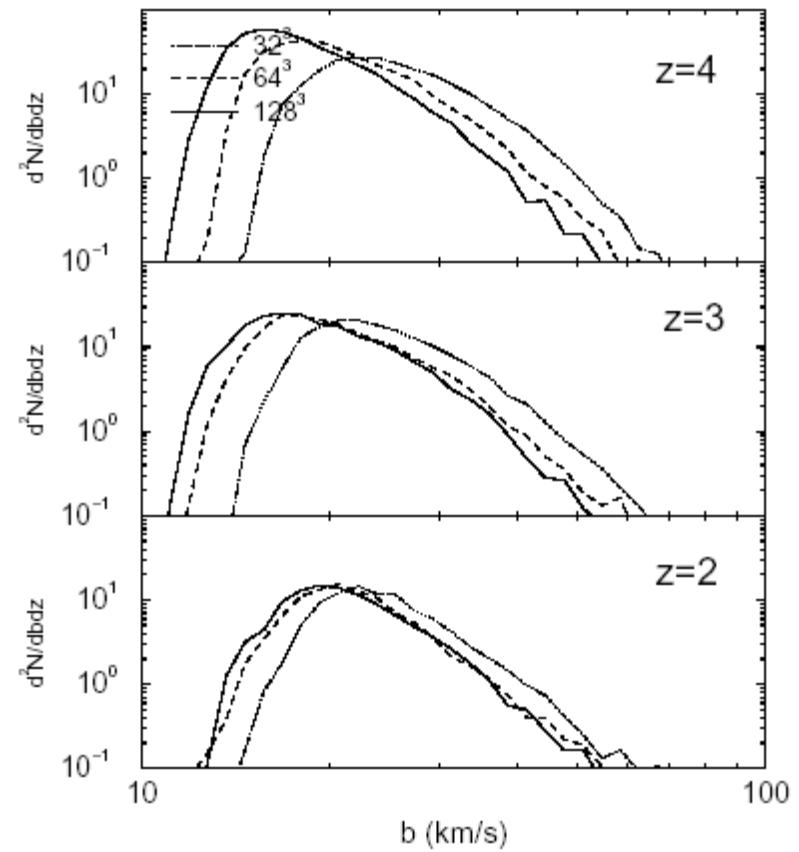
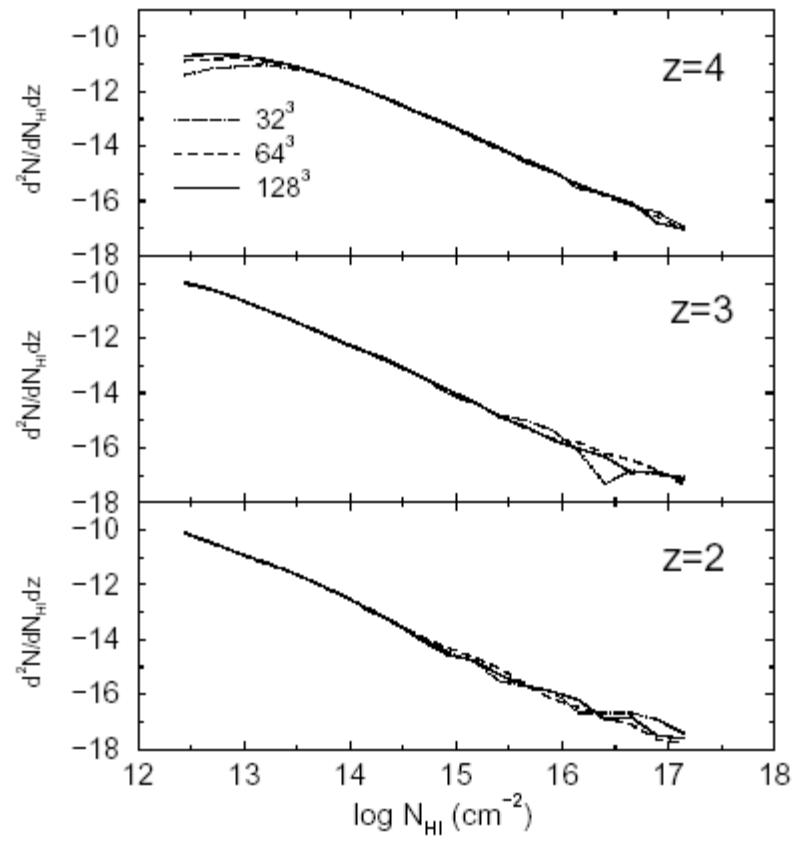
Bryan et al. (1999)

# Resolution Effects

No. 1, 1999

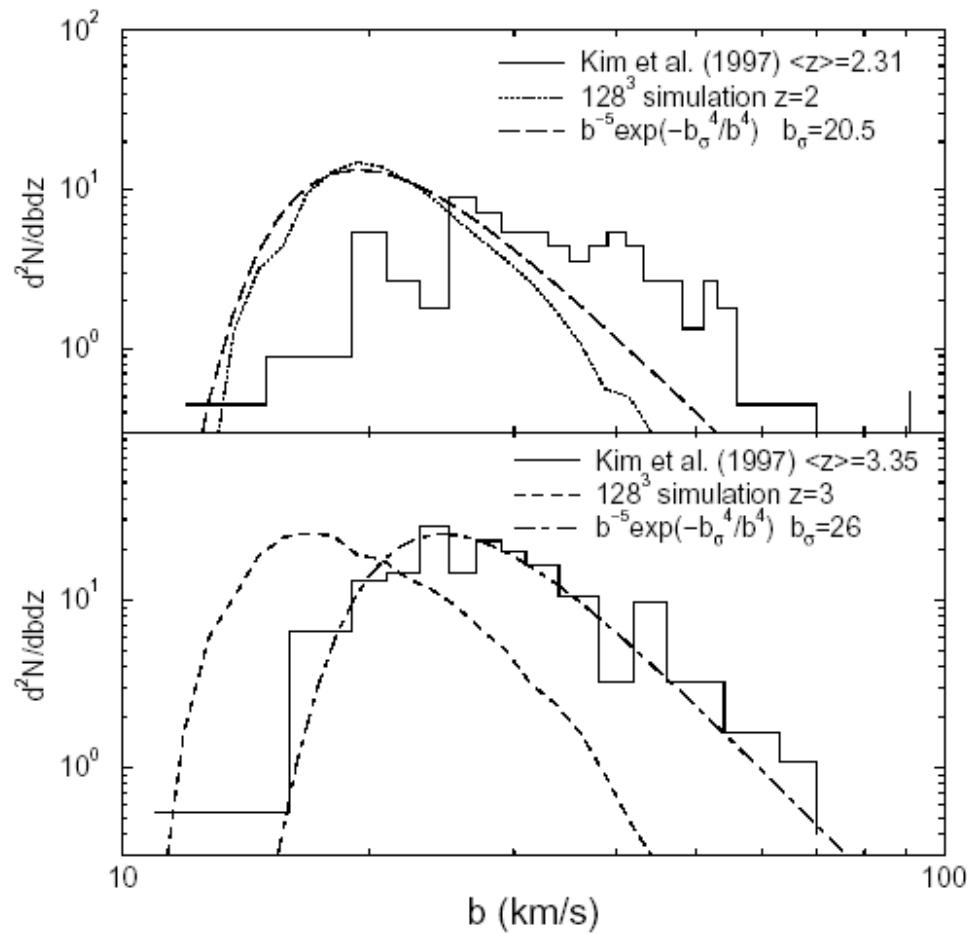
RESOLVING THE Ly $\alpha$  FOREST

17



Bryan et al. (1999)

# The Case for Extra Heating



Bryan et al. (1999)

# “Theory” of the Ly $\alpha$ Forest

- EOS of the IGM (Hui & Gnedin 1997)
  - Photo-heating balances adiabatic expansion cooling

$$T = T_0 (\rho_b / \bar{\rho}_b)^{\gamma-1}$$
$$T_0 \propto (\Omega_b h / \sqrt{\Omega_m})^{1.7}, z \gg z_{reion}$$
$$1.3 \leq \gamma \leq 1.6$$

# “Theory” of the Ly $\alpha$ Forest

- Ionization equilibrium

$$n(HI)\Gamma_{HI} = n_e n_p \alpha(T) \propto \rho_b^2 \alpha(T)$$

$$n(HI) \propto \rho_b^2 \alpha(T) / \Gamma_{HI}$$

$$\Gamma_{HI} = \int_{\nu_{HI}}^{\infty} 4\pi J(\nu) \sigma_{HI} \frac{d\nu}{h\nu}$$

# “Theory” of the Ly $\alpha$ Forest

- Optical depth (Croft et al. 1998)

$$\tau \propto n(HI)\sigma_{Ly\alpha} \propto \rho_b^2 \alpha(T) / \Gamma_{HI}$$

$$\alpha(T) \propto T^{-0.7} \propto [T_0(\rho_b / \bar{\rho}_b)^{\gamma-1}]^{-0.7}$$

$$\therefore \tau = A(\rho_b / \bar{\rho}_b)^\beta, \text{ where } \beta = 2.7 - 0.7\gamma$$

$$A = 0.946 \left( \frac{1+z}{4} \right)^6 \left( \frac{\Omega_b h^2}{0.0125} \right)^2 \left( \frac{T_0}{10^4 K} \right)^{-0.7}$$

$$\times \left( \frac{\Gamma_{HI}}{10^{-12} s^{-1}} \right)^{-1} \left( \frac{H(z)}{100 km/s/Mpc} \right)^{-1}$$

# Cosmological Parameter Studies

- Fully hydrodynamic
  - Input:  $\{\Omega_i, h, n, \sigma_8, J(v, z)\}$
  - Output: baryonic fields  $(\rho_b, T, v) \rightarrow$  spectra
  - $T(\rho_b)$  and observational diagnostics completely determined; e.g.,  $\langle F \rangle$ ,  $P_F(k)$
- Hydro-PM and pseudo-hydro
  - Input:  $\{\Omega_i, h, n, \sigma_8, \langle F \rangle, T_0, \gamma\}$
  - Output: spectra
  - N.B. intrinsic scatter in  $\rho_b/\rho_{dm}$  and  $T(\rho_b)$  missing

# Early Hydro Studies

(Machacek et al. 2000)

$$\sigma_{34}^2 = \int_0^\infty P(k) e^{-2k^2/k_{34}^2} \frac{k^2 dk}{2\pi^2}$$

$$k_{34} = 34\Omega_0^{1/2} h \text{ Mpc}^{-1}$$

Gnedin (1998)

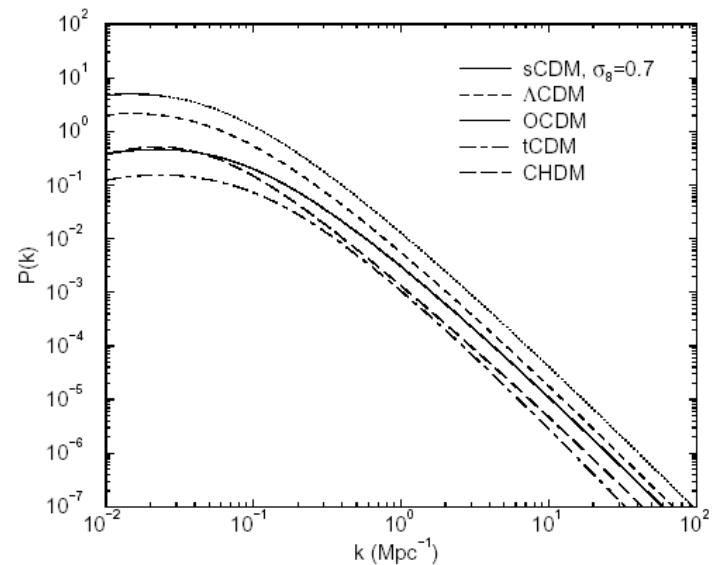
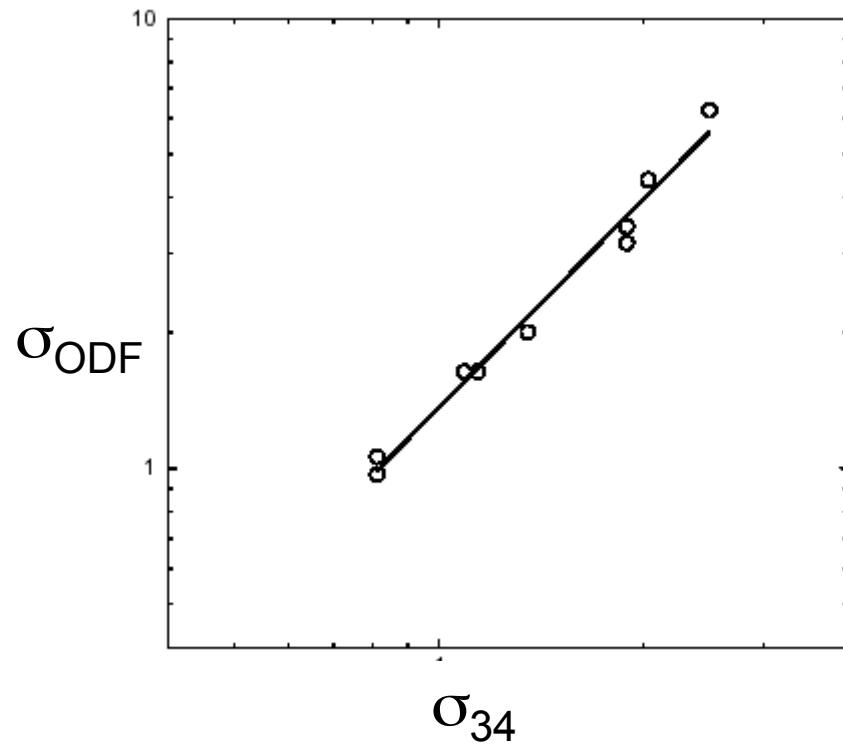
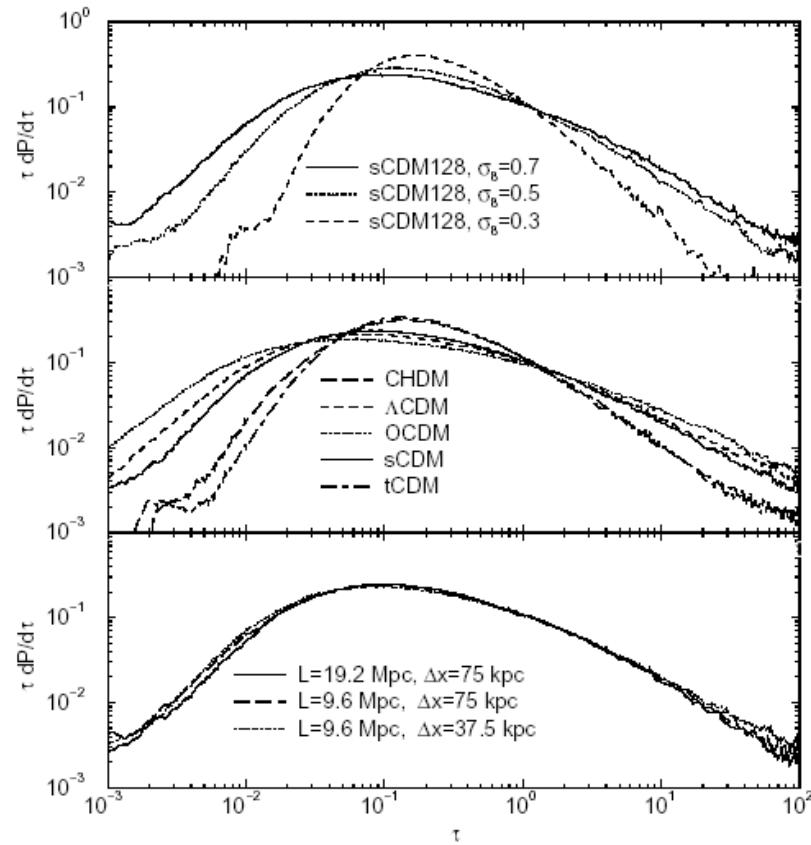


TABLE 1  
PHYSICAL PARAMETERS OF THE DIFFERENT COSMOLOGICAL MODELS.

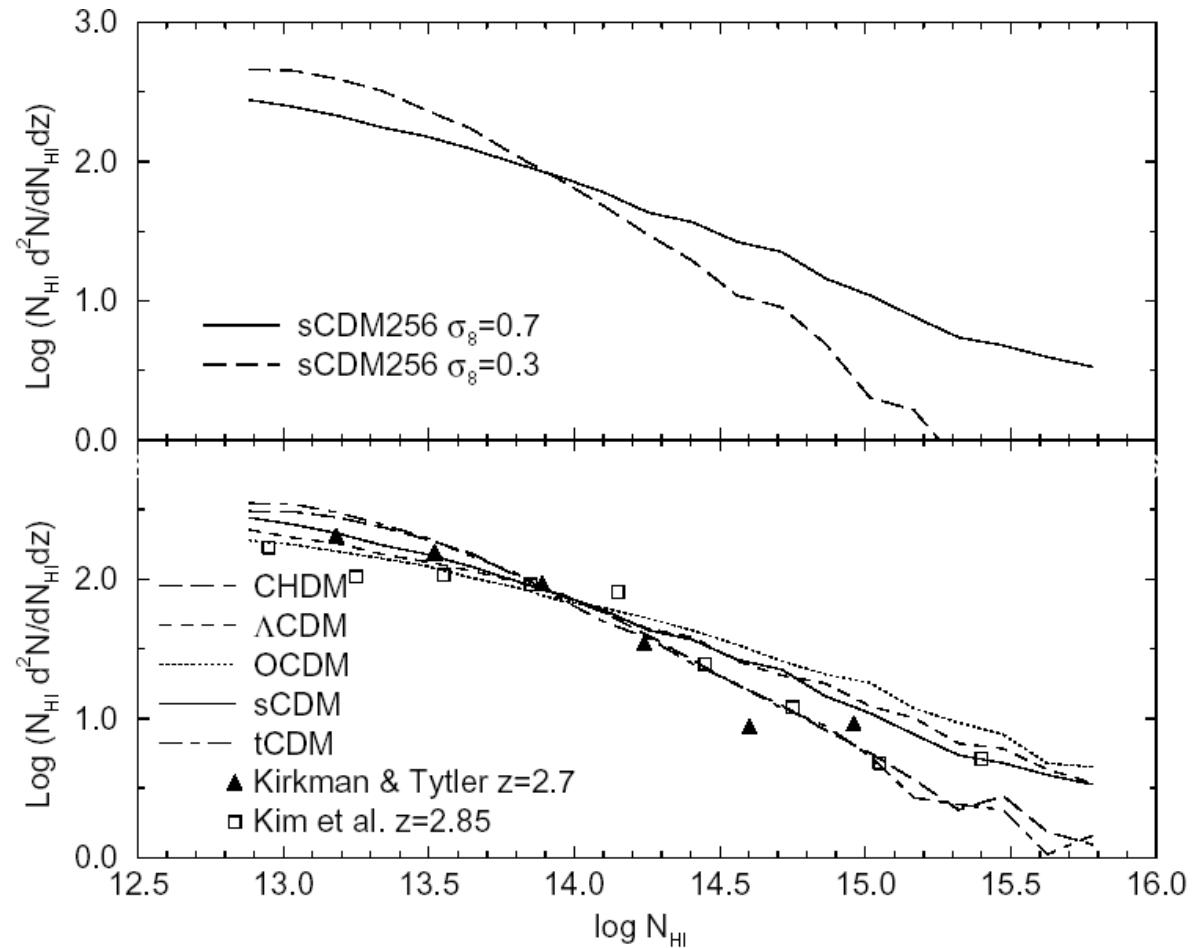
Model	$\Omega_0$	$\Omega_\Lambda$	$q_0$	$\Omega_b$	$h$	$n$	$\sigma_{8h^{-1}}$	$\Delta x$ (kpc)	$\Omega_B h^2$	$\sigma_{34}$
sCDM .....	1	0	0.5	0.06	0.5	1	0.7	37.5	0.015	1.89
$\Lambda$ CDM .....	0.4	0.6	-0.4	0.0355	0.65	1	1.0	37.5	0.015	2.03
OCDM .....	0.4	0	0.2	0.0355	0.65	1	1.0	37.5	0.015	2.50
tCDM .....	1	0	0.5	0.07	0.6	0.81	0.5	37.5	0.025	1.09
CHDM .....	1	0	0.5	0.07	0.6	0.98	0.7	75	0.025	1.14

# Correlation of $\sigma_{\text{ODF}}$ and $\sigma_{34}$



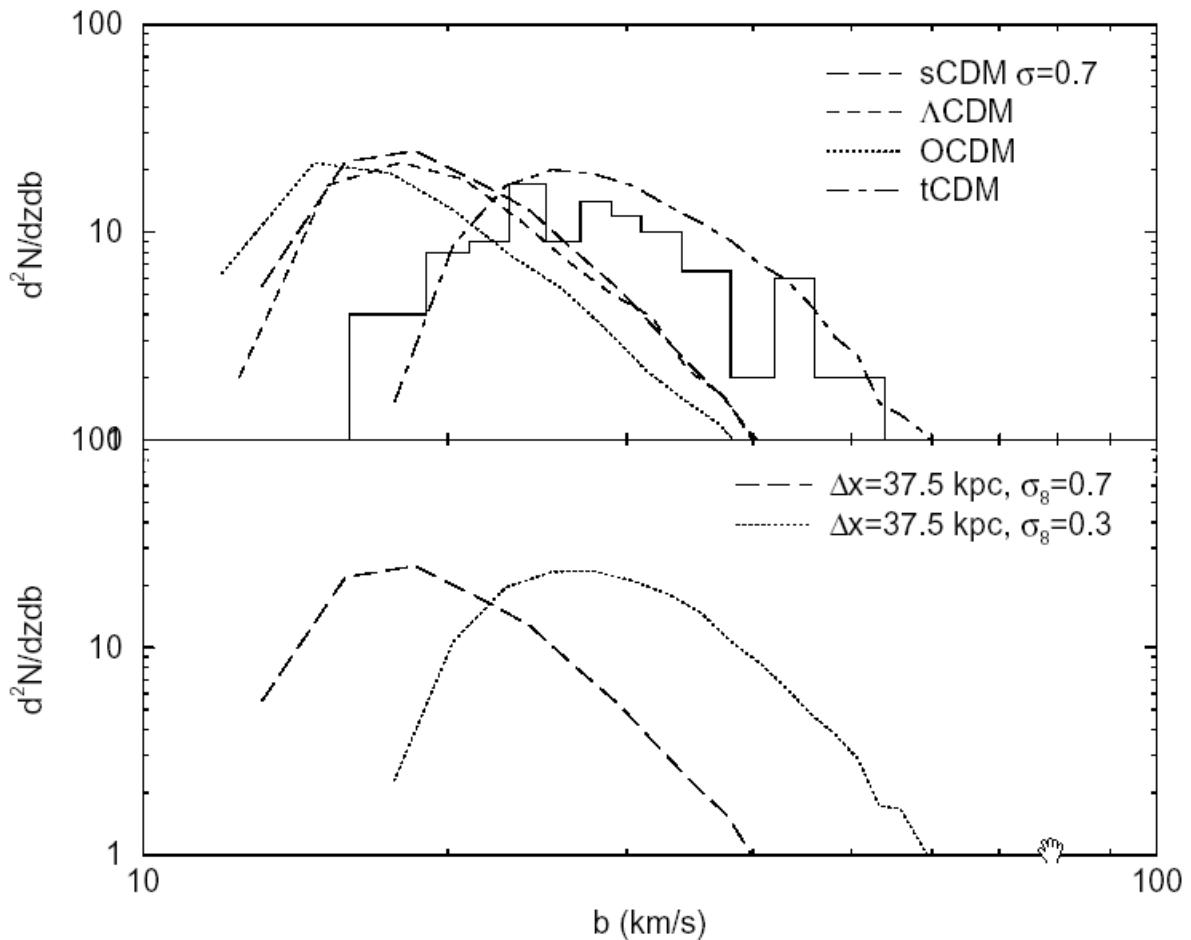
Machacek et al. (2000)

# Column Density Distribution



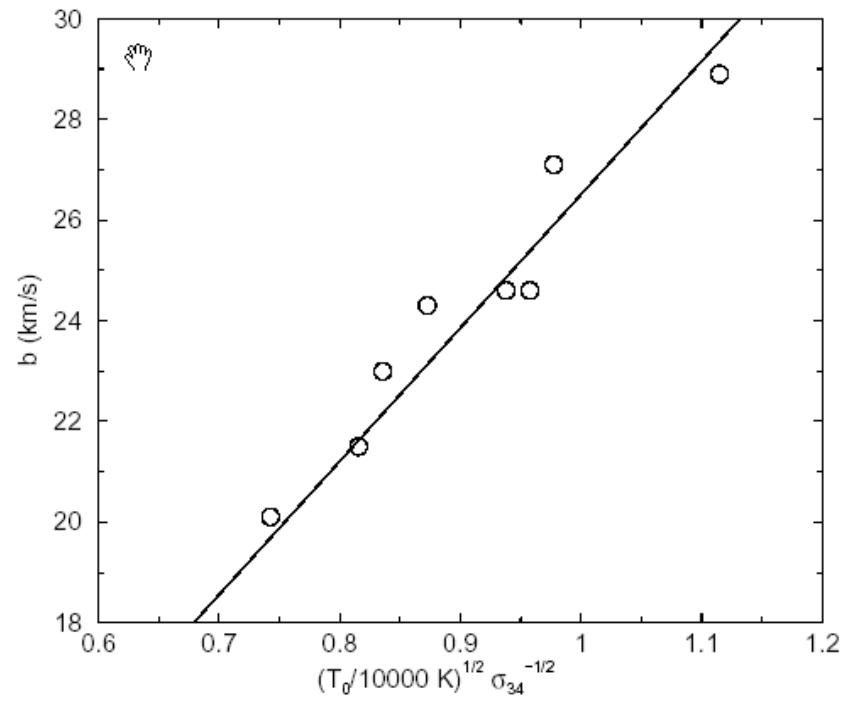
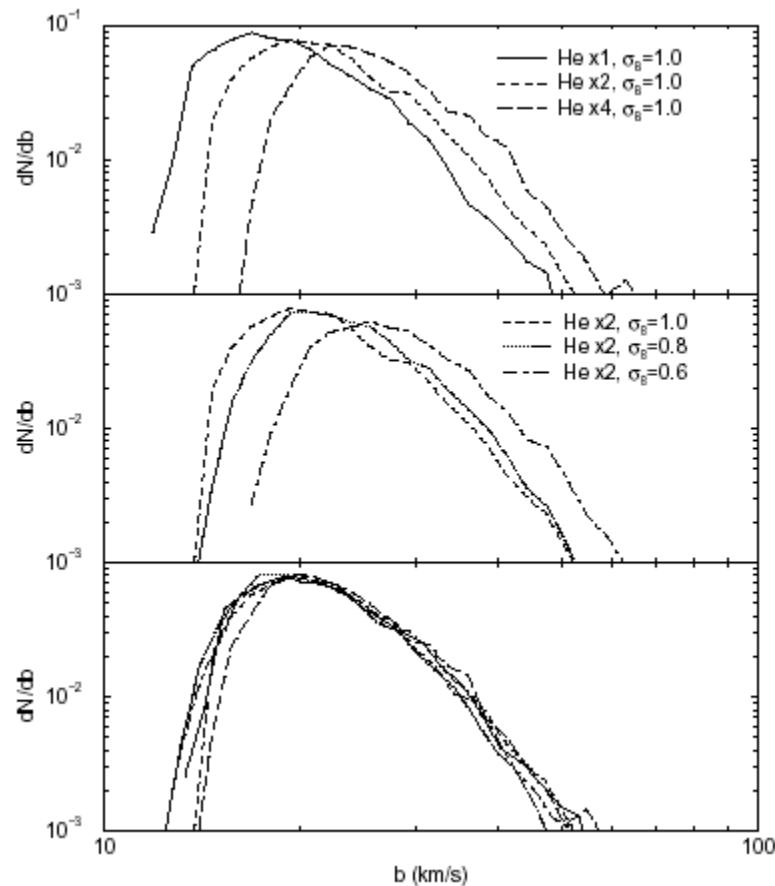
Machacek et al. (2000)

# Linewidth Distribution



Machacek et al. (2000)

# Temperature-Power Degeneracy



Bryan & Machacek (2000)

# Recovery of $P(k)$ from the Flux Power Spectrum $P_F(k)$ (Croft et al. 1998, 1999, 2002)

- Basics (Kaiser & Peacock 1991)

$$P_{1D}(k) = \frac{1}{2\pi} \int_k^\infty P(k') k' dk'$$
$$P(k) = -\frac{2\pi}{k} \frac{d}{dk} P_{1D}(k)$$

- Definitions
- $$\delta_F(x) = (F(x) - \langle F(x) \rangle) / \langle F(x) \rangle$$
- $$\delta_F(k) = \frac{1}{2\pi} \int \delta_F(x) e^{-ikx} dx$$
- $$P_F^{1D}(k) = \langle \delta_F^2(k) \rangle$$
- $$P_F(k) = -\frac{2\pi}{k} \frac{d}{dk} P_F^{1D}(k), \quad \Delta^2(k) = k^3 P(k)$$

# Croft et al., cont'd

- Anzatz

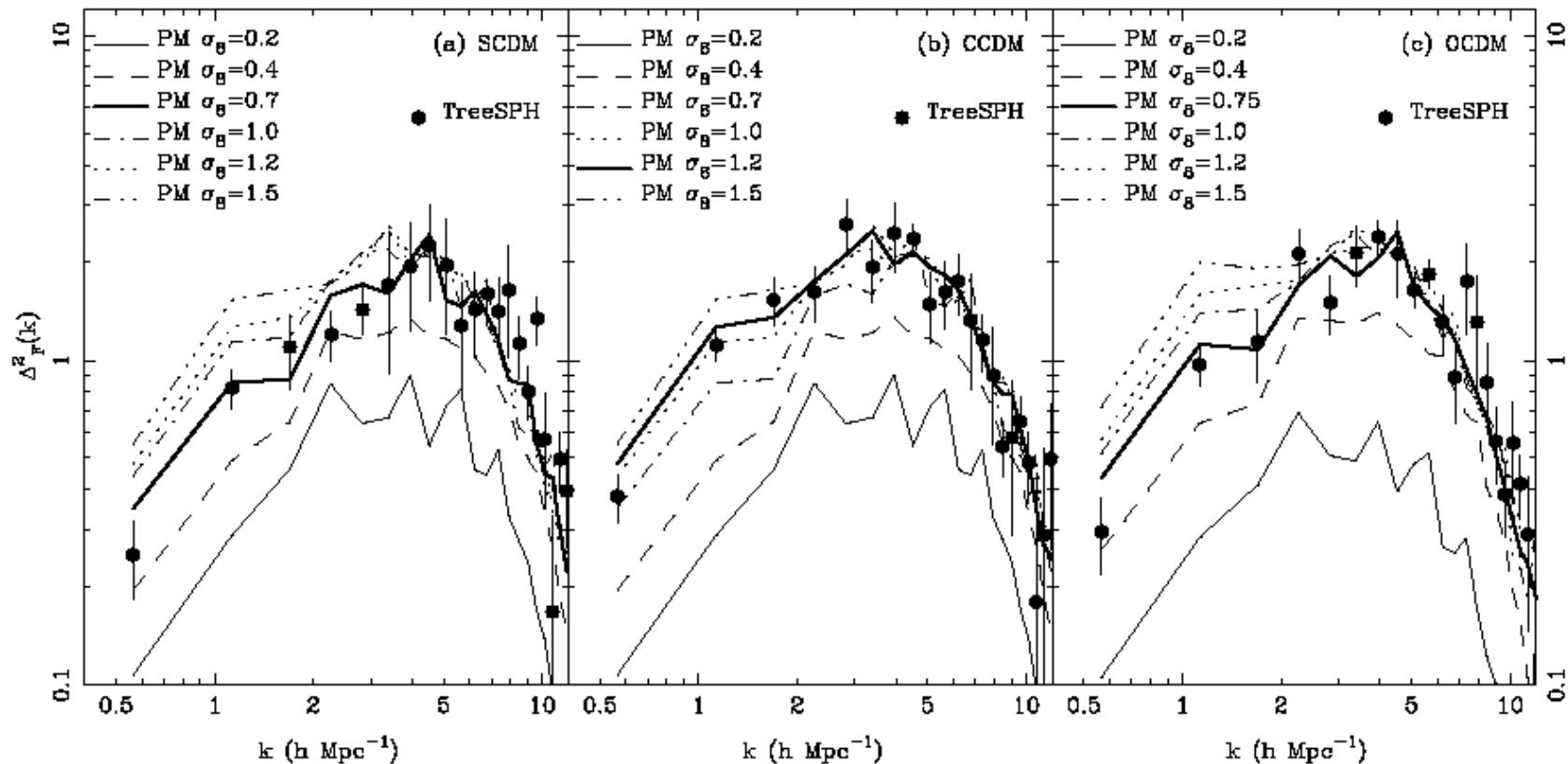
$$P_F(k) = b^2(k)P(k)$$

- Approach
  - Run parameter survey pseudo-hydro simulations to find  $b(k)$ ; check against hydro simulation
- In general  $b(k)=b(k;\text{parameters})$
- Claim:  $b$  asymptotes at small  $k$ ; depends only on  $A$  which can be set by mean flux

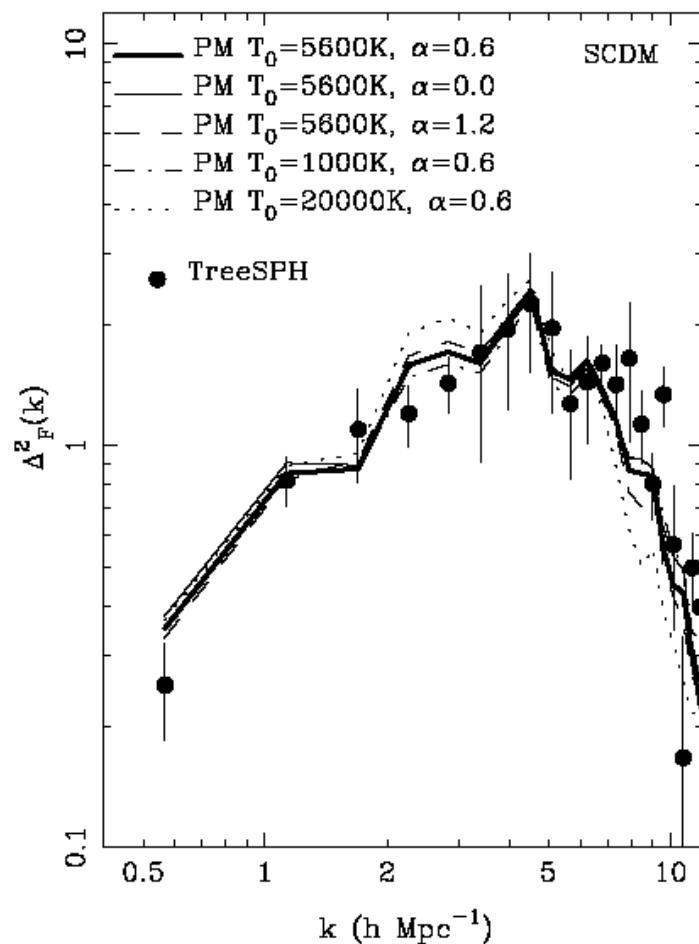
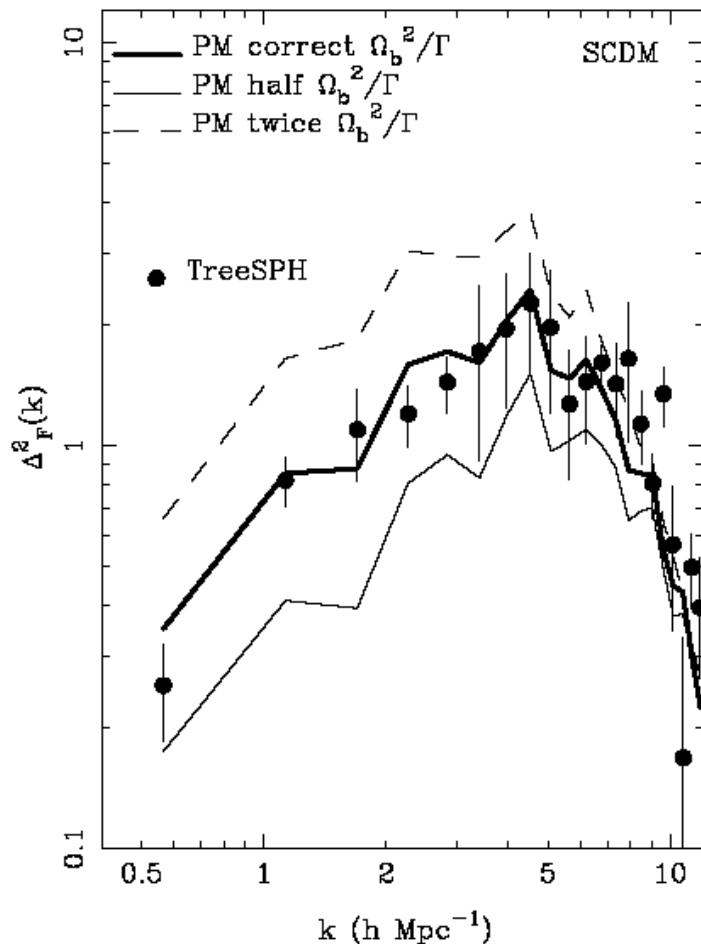
# Sensitivity to $\sigma_8$

$\langle \rangle^m$

CROFT ET AL.

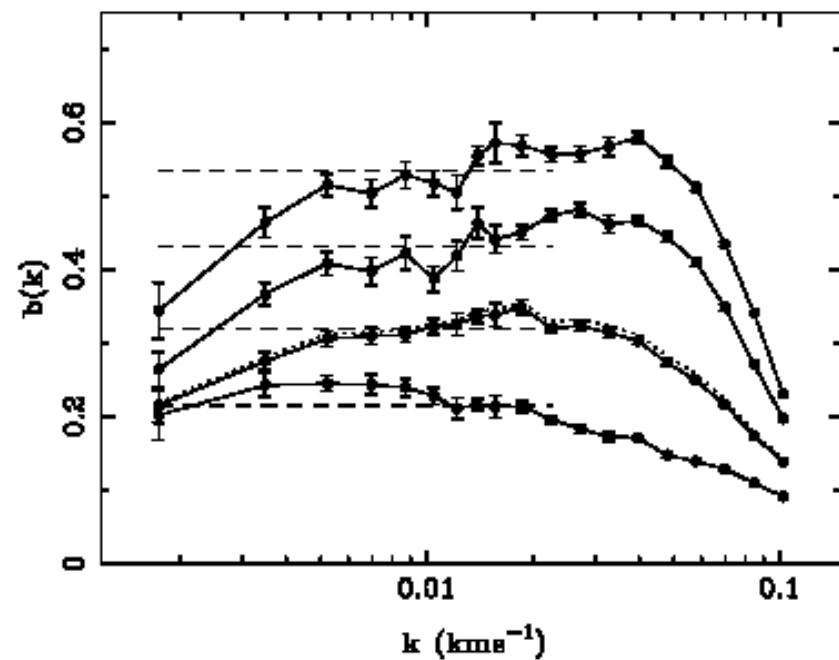
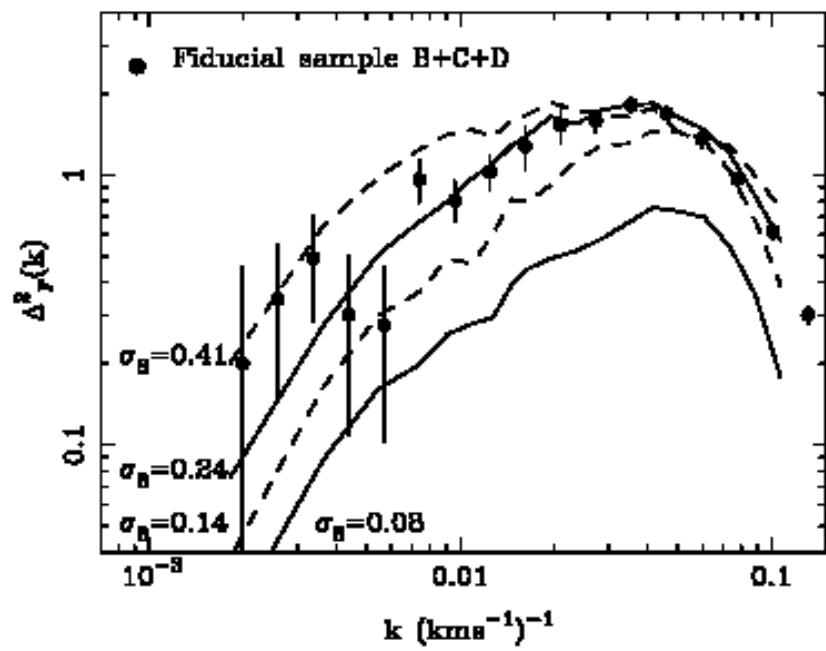


# Sensitivity to $\langle F \rangle$ Insensitivity to $T_0$ and $\gamma$ for fixed $\langle F \rangle$

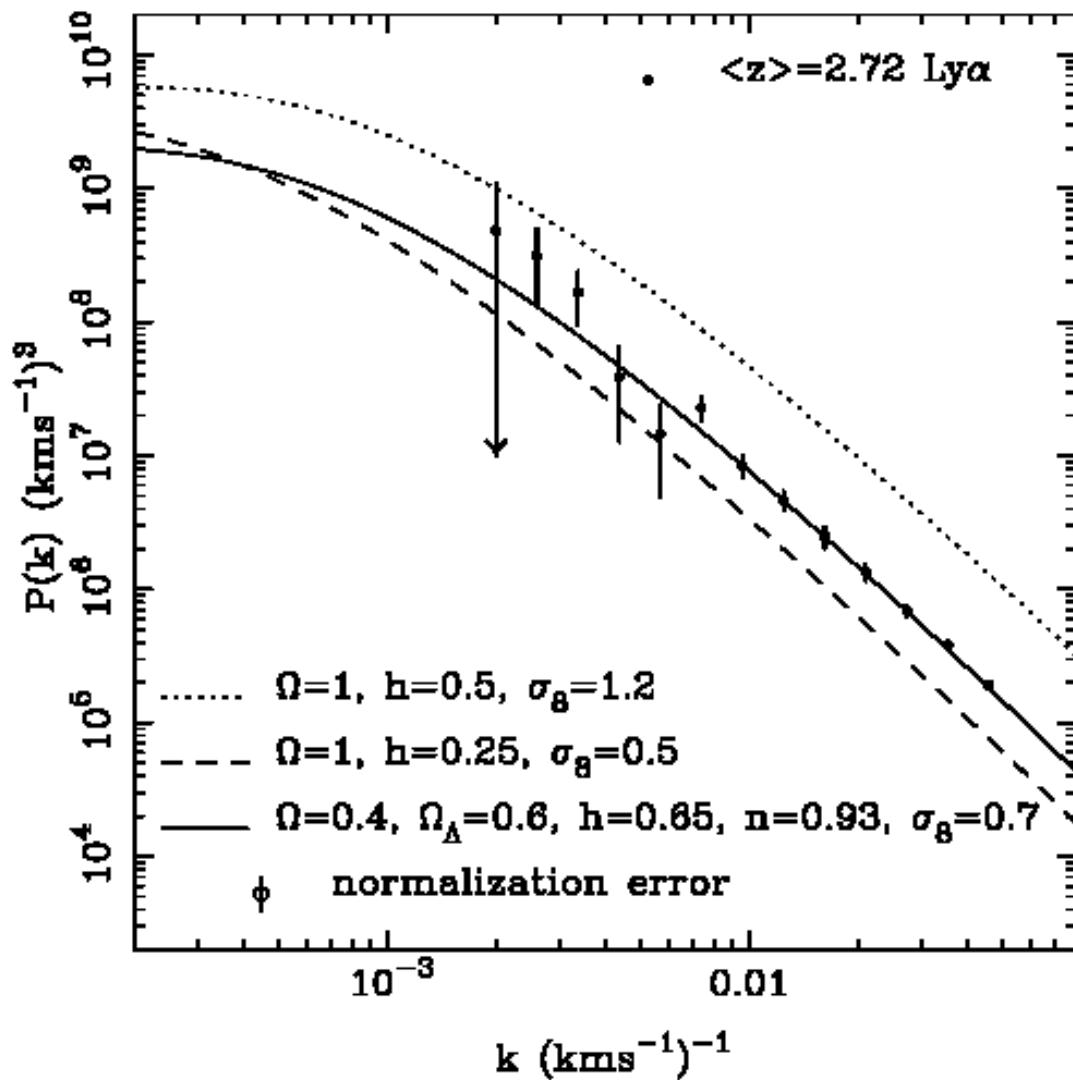


Croft et al. (1998)

$$b(k) = \sqrt{P(k) / P_F(k)}$$



# Result (Croft et al. 2002)



# Caution: Effect of Continuum Fitting

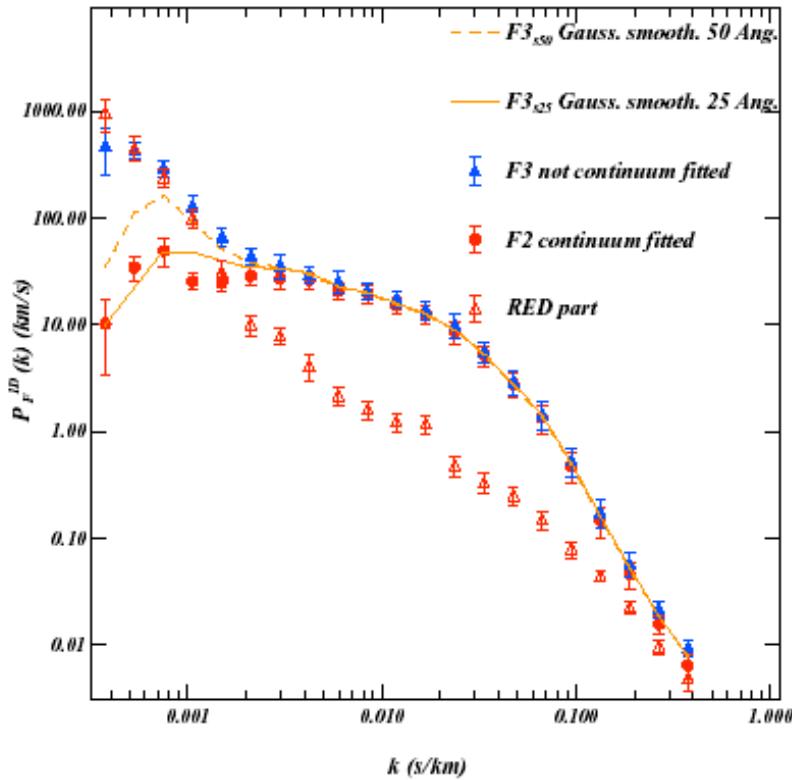


Figure 2. Effect of continuum fitting on the 1D flux power spectrum. Circles are for the continuum fitted spectrum  $F2 = e^{-\tau} / \langle e^{-\tau} \rangle - 1$ , solid triangles are for the not continuum fitted spectrum  $F3 = I_{\text{obs}} / \langle I_{\text{obs}} \rangle - 1$ . Dashed and solid line are for spectra smoothed with a Gaussian window of 25 and 50 Å width, respectively, as described in the text. Error bars denote the  $1\sigma$  errors of the mean values. Open triangles show the flux power spectrum of  $F3$  for the region redwards of the Lyman- $\alpha$  emission line (1265.67 - 1393.67 Å).

Kim et al. (2004)

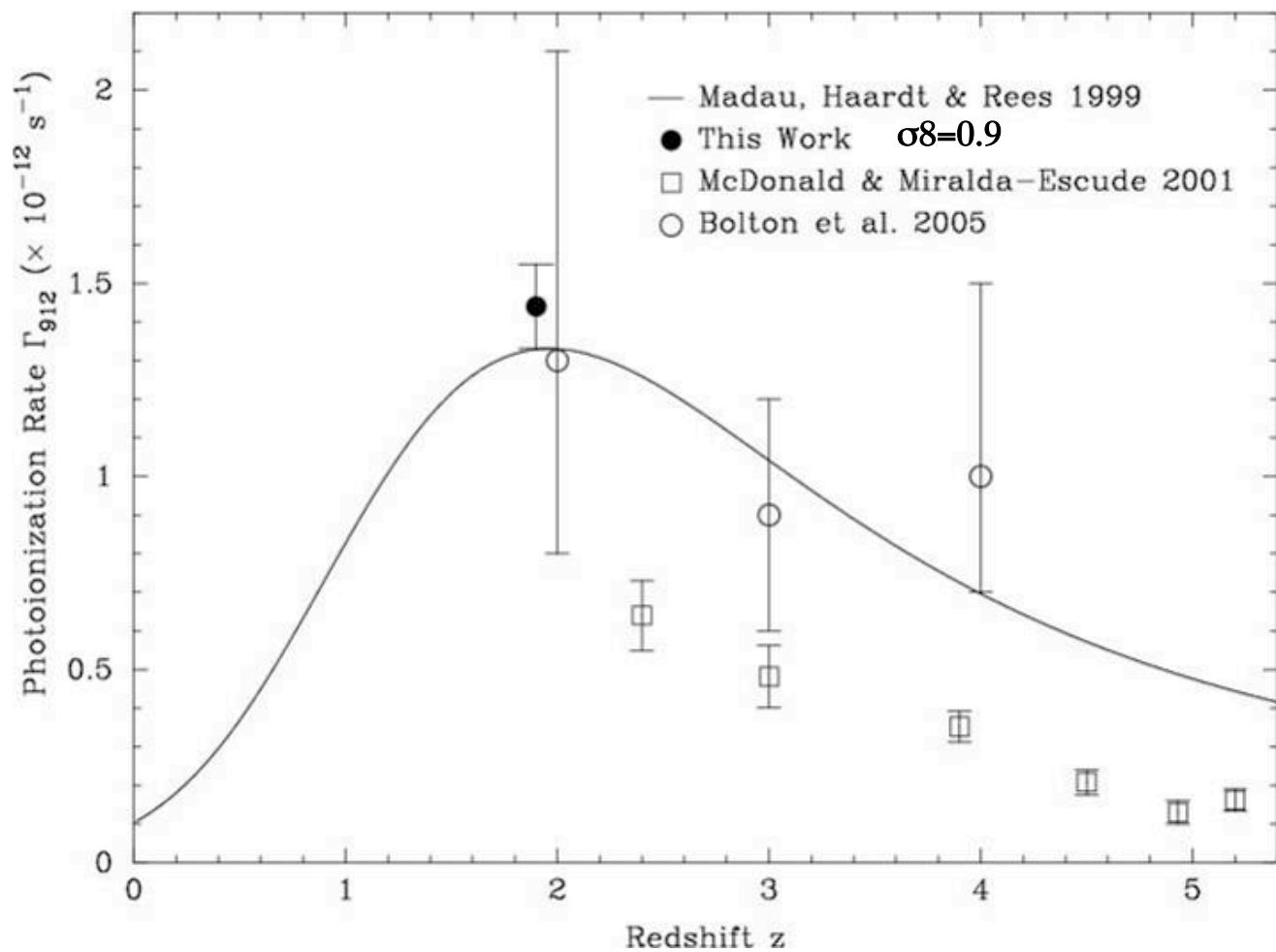
# Improvements to Continuum Fitting (Tytler et al. 2004)

- Unabsorbed low-z HST spectra classified using principal component analysis (Suzuki et al. 2004)
- Artificial Ly $\alpha$  forest spectra created by synthesizing unabsorbed spectra, then super-imposing lines and noise
- 4 undergrads trained to fit continuum of artificial spectra; biases measured
- 77 Lick spectra continuum fit, corrected for biases; metal lines and DLAs removed statistically
- Improved  $D_A = 0.128 \pm 0.009$  at  $z=1.95$

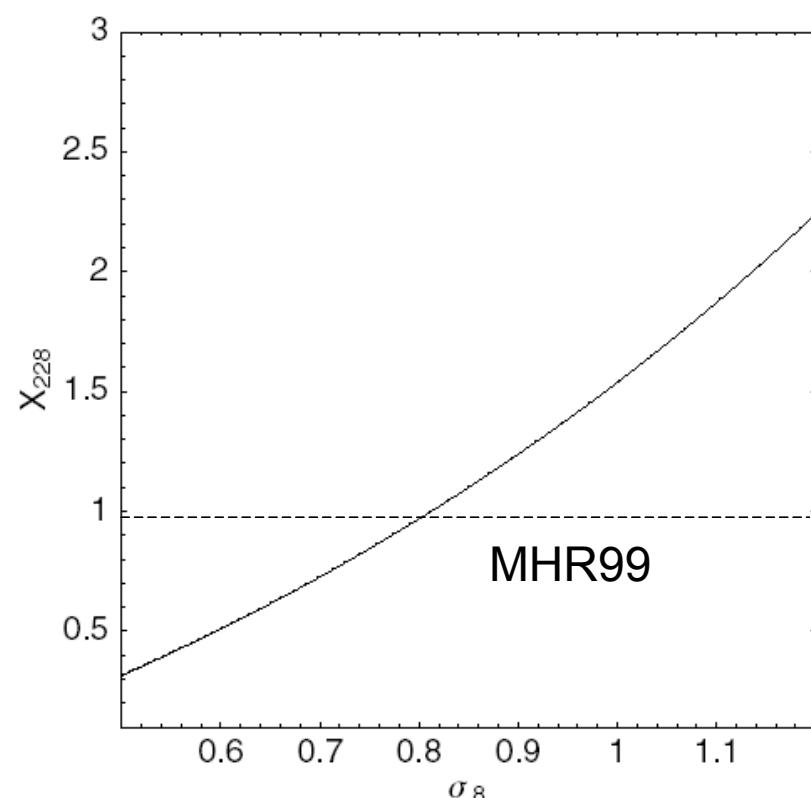
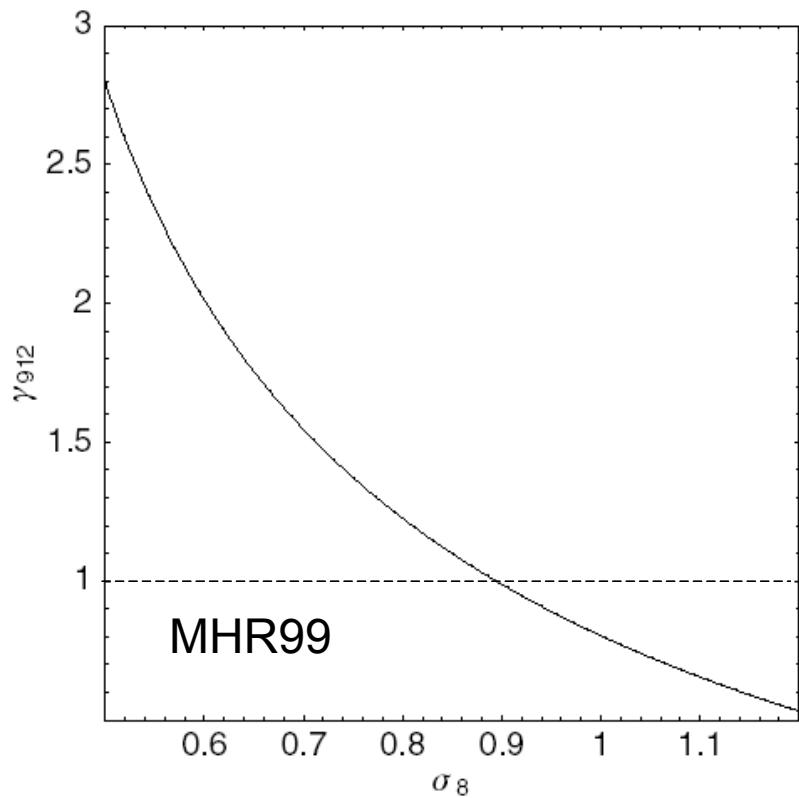
# Concordance Model of the Ly $\alpha$ Forest at z=1.95 (Jena et al. 2005)

- Suite of 40 fully hydrodynamical simulations using WMAP parameters ( $\Omega_m=0.27$ ,  $\Omega_\Lambda=0.73$ )
- Vary  $\sigma_8$ ,  $J(v, z)$ , box size, resolution
- Measure  $\langle F \rangle$ ,  $b_\sigma$ ,  $P_F(k)$  at  $k=10^{-2}, 10^{-1.5}, 10^{-1}$
- Deduce scaling relations: Outputs=f(Inputs)
- Compare with best available data
- Deduce best fit parameters  $\sigma_8, \Gamma_{912}, X_{228}$
- **Find**: cannot reduce  $\sigma_8$  parameter degeneracy with only small-scale power  $\rightarrow \Gamma_{912}(\sigma_8), X_{228}(\sigma_8)$

# HI Photoionization Rate $\Gamma_{912}$

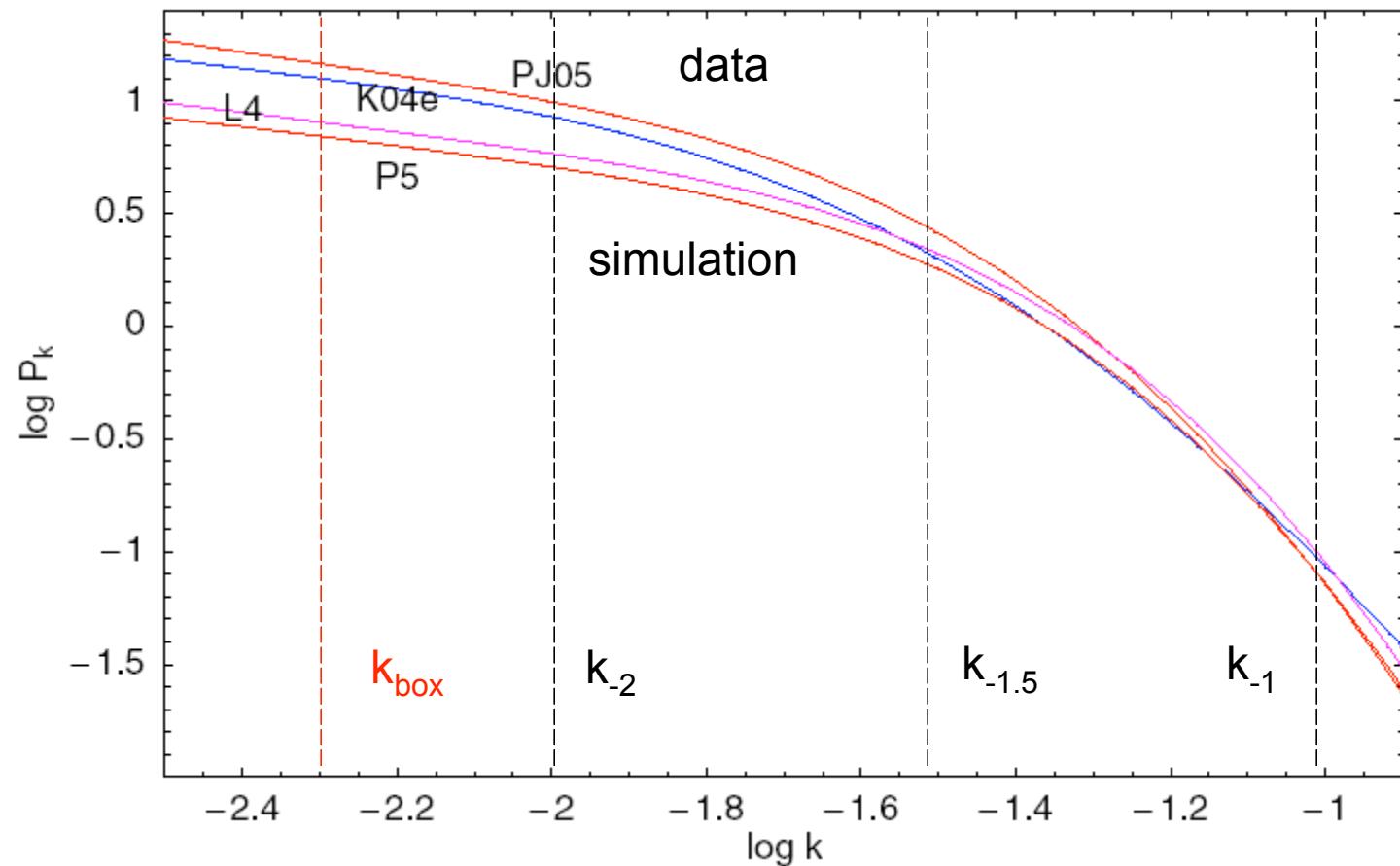


# Dependence on $\sigma_8$



Jena et al. (2005)

# Flux Power Spectrum



Jena et al. (2005)

# Outlook

- Ly $\alpha$  forest shows great promise for precision cosmology
- Temperature-power degeneracy is still lurking (the mean flux depends on the mean temperature)
- Precision will require precision continuum fitting over long  $\Delta z$  and comparison with simulations in comparable  $\Delta z$